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Gulf Coast Salt Domes
Geologic Area Characterization Report
Introduction

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Volume I
Technical Report

July 1982

Law Engineering Testing Company
2749 Delk Road, S.E.
Marietta, GA 30067

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Office of Nuclear Waste Isolation

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ABSTRACT

This volume introduces Geologic Area Characterization Reports (ACRs) for the Gulf Interior Region Salt Domes. Overviews of the National Waste Terminal Storage Program and the Site Screening Process are presented. This volume also summarizes the regional geologic setting and presents a condensed review of the findings of area-phase investigations.

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FOREWORD

The National Waste Terminal Storage (NWTS) program was established in 1976 by the Department of Energy's (DOE) predecessor agency, the Energy Research and Development Administration (ERDA), to develop the technology and provide the facilities for the safe, environmentally acceptable, permanent disposal of high-level nuclear waste (HLW).

DOE's responsibility for the long-term management of highly radioactive nuclear wastes is defined by federal laws, which specify that DOE must provide facilities for the successful isolation of HLW from the environment in federally licensed and federally owned repositories for as long as the wastes represent a significant hazard.

Highly radioactive nuclear wastes include wastes from both commercial and defense sources, such as spent (used) fuel from nuclear power reactors, accumulations of wastes remaining from production of nuclear weapons, and solidified wastes from fuel reprocessing.

To meet its major objective of isolating high-level wastes, DOE is developing a technical program that will meet all relevant radiological protection criteria as well as other applicable regulatory requirements.

NWTS activities include providing the technology and facilities for the other terminal isolation of these wastes. DOE's program emphasizes disposal in mined repositories deep underground in stable geologic formations. Several types of rock are

being studied in several states. Rock types include bedded salt deposits, salt domes, basalt (solidified lava), tuff (compacted volcanic ash), and "crystalline" rocks*.

Steps leading to the permanent disposal of HLW are:

- Studying, characterizing, and recommending potential sites for repositories
- Designing, licensing, and operating commercial repositories
- Providing waste packaging facilities
- Developing transportation requirements
- Developing the technology to support these steps
- Studying alternative disposal methods as long-range options to the geologic disposal program.

Four separate, but coordinated, projects are involved in the HLW disposal program: the Office of Nuclear Waste Isolation (ONWI), the Basalt Waste Isolation Project (BWIP) at DOE's Hanford Reservation in Washington state, the Nevada Nuclear Waste Storage Investigations (NNWSI) at the federal Nevada Test Site, and the Subseabed Disposal Project. ONWI, BWIP, and NNWSI focus on different rock types and conduct studies in site evaluation, technology development, facility design, and field testing. They share data and information of general benefit. ONWI coordinates site exploration studies on non-DOE land. The Subseabed Disposal Project is assessing the technical, environmental, engineering,

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*"Crystalline" rock is a general term for igneous and metamorphic rocks, as opposed to sedimentary rocks. Granite is one type of crystalline rock.

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and institutional feasibility of disposing of processed highly radioactive nuclear waste and/or repackaged spent fuel in geologic formations beneath the sediments of the oceans.

Identifying possible sites for geologic repositories and evaluating their potential involves the collection and analysis of detailed geologic and environmental data and comparison of the data against predetermined site performance criteria (i.e., geologic characteristics, environmental protection, and socioeconomic impacts). The site selection process consists of a series of increasingly detailed steps to obtain environmental and geologic information. The steps are: national survey of one or more rock types with potential for waste containment; identification of regions containing potentially suitable rock types; recommendation of study areas, and then locations. Then at the conclusion of each screening step, the focus narrows to smaller land areas, while the amount of data collected increases. Screening steps will identify potential sites at several locations, leading to the next phase, site characterization. The purpose of site characterization is to assess a site's suitability for a repository. The process culminates in DOE's application to the U.S. Nuclear Regulatory Commission (NRC) for authorization to construct and operate the first repository.

The first federal repository for the isolation of high-level nuclear wastes is expected to be in operation between 1998 and 2006, following the site selection process outlined, field testing and technology development programs, and fulfillment of licensing requirements. DOE expects to choose one site from

among several qualified sites and apply to NRC in 1988 for a license to construct the first repository. Several repositories are planned.

Throughout the repository siting and construction process, opportunities are provided for public and peer review and comment. DOE maintains an open information program for nuclear waste management activities and is committed to a policy of consultation with state and local officials. Information is provided to both technical and nontechnical groups and to governmental officials through review of major reports, briefings, conferences, public meetings, and printed material. Additional opportunities for public input will occur at public hearings and reviews that are part of the licensing process.

Several documents and statements provide policy and technical guidance in the definition and planning of the NWTS program:

1. President's Nuclear Policy Statement, October 8, 1981.
2. DOE Record of Decision (to adopt the mined geologic disposal strategy and develop repositories), May 14, 1981.
3. National Plan for Siting High-level Radioactive Waste Repositories and Environmental Assessment (Draft), February, 1982.
4. Final Generic Environmental Impact Statement (FEIS) (U.S. DOE, 1980a)
5. Proposed Rulemaking on the Storage and Disposal of Nuclear Waste (Waste Confidence Rulemaking) -

Statement of Position of the U.S. Department of Energy, April 15, 1980b.

6. Proposed Rulemaking on the Storage and Disposal of Nuclear Waste (Waste Confidence Rulemaking) - Cross-Statement of Position of the U.S. Department of Energy, September 5, 1980c.
7. Report to the President by the Interagency Review Group on Nuclear Waste Management, March, 1979 (IRG, 1979).
8. Earth Science Technical Plan for Mined Geologic Disposal of Radioactive Waste (ESTP), U.S. DOE et al, 1979.

Both the IRG Report and the FEIS evaluate alternative waste disposal processes and conclude that mined geologic disposal will be the earliest one available. The IRG report recommends that near-term program activities should be predicated on the tentative assumption that the first disposal facilities will be geologic repositories. The FEIS provides a detailed evaluation of ten methods for waste disposal and concludes that the technology for emplacement of radioactive wastes in geologic formations can likely be developed and applied with minimal environmental consequences. The ESTP, which is the product of a cooperative effort by DOE and the U.S. Geological Survey (USGS), furnishes detailed programmatic guidance for implementing research addressing specific earth science issues associated with geologic waste disposal.

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GLOSSARY OF GEOLOGICAL TERMS

AGGRADATION - process of building up a surface by deposition.

ALLUVIUM - a general term for clay, silt, sand, gravel or similar unconsolidated detrital material deposited during comparatively recent geologic time by a stream or other body of running water; adj. alluvial.

ANGULAR UNCONFORMITY - an unconformity in which the younger overlying sediments rest upon the eroded surface of tilted or folded older rocks.

ANHEDRAL - a crystal in which the crystal faces are neither distinct nor characteristic of the particular mineral or element.

ANHYDRITE - a mineral consisting of anhydrous calcium sulfate: $CaSO_4$.

ANHYDROUS - a substance that is completely or essentially without water; an anhydrous mineral contains no water in chemical combination.

ANTICLINE - a fold, the core of which contains stratigraphically older rocks; it is convex upward; adj. anticlinal; ant. syncline.

AQUICLUDE - a body of relatively impermeable rock that is capable of absorbing water slowly but functions as an upper or lower boundary of an aquifer, and does not transmit water rapidly enough to supply a well or spring; "confining bed" is preferred.

AQUIFER - a body of rock that contains sufficiently saturated permeable material to yield significant quantities of water to wells and springs.

AQUIFUGE - an impermeable body of rock; "confining bed" is preferred.

AQUITARD - a body of impermeable material stratigraphically adjacent to one or more aquifers; "confining bed" is preferred.

AREAL MAP - a geologic map showing the horizontal extent and distribution of rock varieties or rock units exposed at the surface.

ARENACEOUS - sediment or sedimentary rock consisting entirely or partially of sand-size fragments, or having a sandy texture or the appearance of sand.

GLOSSARY OF GEOLOGICAL TERMS (Continued)

ARGILLACEOUS - sediment or sedimentary rock consisting entirely or in part of clay-size particles or clay minerals.

ASPHALTIC ROCK - a porous rock that has been impregnated naturally with asphalt.

BENTONITE - a general term for the montmorillonitic clay minerals derived from volcanic ash.

BIOSPHERE - all the area occupied by or favorable for occupation by living organisms including parts of the lithosphere, hydrosphere, and atmosphere. For considerations related to salt dome hydrology, the scope of the biosphere is expanded to include man and his food chain, i.e., from drillable depths, ±9,144 meters (± 30,000 ft) deep in the earth's crust, to the base of the stratosphere.

BIOSTRATIGRAPHY - stratigraphy based on the paleontologic aspects of rocks or stratigraphy with paleontologic methods.

BITTERNS - a natural solution, in an evaporite basin, that resembles a saltworks liquor, especially in its high magnesium content.

BLOCK FAULTING - a type of normal faulting in which the crust is divided into structural or fault blocks of different elevations and orientations.

BLOWOUTS - gaseous outbursts that may occur within a salt mine at the time of blasting and are confined to anomalous zones.

BOUDINAGE - a structure in which an original, continuous, competent layer or bed between less competent layers has stretched, thinned, and broken at regular intervals into bodies resembling boudins (sausage links) elongated parallel to the fold axis.

BOUGUER ANOMALY - a gravity anomaly calculated by allowing for the attraction effect of topography but not for that of isostatic compensation.

BOUNDARY SHEAR ZONES - a zone that forms the boundary between a spine of salt and the outside of the salt dome, or between two spines.

BRECCIATED - said of a rock structure marked by an accumulation of angular fragments, or of an ore texture showing mineral fragments without notable rounding.

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GLOSSARY OF GEOLOGICAL TERMS (Continued)

BRINE WELL - a salt well from which water is taken to be evaporated for making salt.

CALCITE - a common rock-forming mineral: $CaCO_3$.

CALIPER LOG - a graphic record which shows, to scale, the diameter of a drilled hole.

CAPABLE FAULT - a fault on which movement at or near the ground surface has occurred at least once within the past 35,000 years, or has had movement of a recurring nature within the past 500,000 years; a fault which has been directly correlated with seismic events.

CAPROCK - a hard rock layer, usually anhydrite, calcite, and gypsum, commonly found overlying the salt stock.

CARBONATE - a sediment formed by the organic or inorganic precipitation from aqueous solution of carbonates of calcium, magnesium or iron.

CARBONIC ACID - A weak naturally occurring acid (H_2CO_3), formed from atmospheric water and carbon dioxide.

CATACLASIS - rock deformation accomplished by fracture and rotation of mineral grains or aggregates without chemical reconstitution.

CLASTIC - a rock or sediment composed principally of broken fragments that are derived from pre-existing rocks or minerals and have been transported individually.

COMMON DEPTH POINT - a point at depth at which seismic reflections are produced at different offset distances on several profiles.

COMPETENT - said of a bed or stratum that is able to withstand the pressures of folding without flowage or change in original thickness.

COMPRESSIVE STRENGTH - a material's resistance to the maximum compressive stress that can be applied to a material, under given conditions, before failure occurs.

CONDUCTANCE - a measurement of salinity or salt (electrolyte) concentration of a fluid.

CONDUCTIVITY - usually refers to electricity or ionic transfer as in an electrolyte; or thermal conductivity, transfer of heat.

CONFINING BED - a zone or bed of impermeable or distinctly less permeable material adjacent to one or more aquifers; see aquitard.

CONFORMABLE - an unbroken sequence of strata in which the layers are formed one above the other in parallel order by regular uninterrupted deposition under the same general conditions.

CONTOUR MAPS - an illustration of the form and distribution of various types of data produced by joining points of equal value; e.g., structural, isopach, topographic.

COQUINA ROCK- a detrital limestone composed wholly or chiefly of mechanically sorted fossil debris; adj. coquinoid.

CORE - a cylindrical or columnar piece of solid rock or section of soil taken as a sample of an underground formation by a special hollow-type drill bit.

CREEP - slow deformation of solid rock resulting from a small, constant stress acting over a long period of time.

CUESTA - a hill or ridge with a gentle slope (dip slope) on one side and a steep slope (scarp face) on the other.

DECLIVITY - a descending slope.

DEGRADATION - the general lowering of the surface of the land by erosive processes.

DELTA - an alluvial deposit, usually triangular, at the mouth of a river.

DENDRITIC DRAINAGE PATTERN - drainage pattern characterized by irregular branching.

DENUDATION - the process of exposing strata by erosion of overlying materials.

DEPOCENTER - an area or site of maximum deposition.

DESOMANTICLINE - a series of structural highs and lows aligned along a linear axis, resembling a chain or string of beads.

DETRITUS - a collective term for loose rock and mineral material that is worn from an older rock by mechanical means and moved from its place of origin.

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GLOSSARY OF GEOLOGICAL TERMS (Continued)

DIAGENESIS - The process by which all the chemical, physical, and biologic changes, modifications or transformations are undergone by a sediment after its initial deposition, and during and after its lithification, exclusive of surficial alteration and metamorphism.

DIAPIR - a dome or anticlinal fold, the overlying rocks of which have been ruptured or pierced by the squeezing out of the plastic core material, such as salt or an incompetant shale.

DIAPIRISM - the process of piercing or rupturing of domes or uplifting overlying rocks by core material, such as salt.

DIP - the angle that a bedding or structural surface makes with the horizontal plane, measured perpendicular to the strike.

DISCONFORMITY - an unconformity in which the older rocks remained essentially horizontal during erosion or cessation of deposition during simple vertical rising and sinking of the crust.

DISSOLUTION - a space or cavity in or between rocks formed by the solution of part of the rock material.

DOME - see salt dome.

DOWNCUTTING - stream erosion in which the cutting is directed in a downward direction.

DOWNDIP - a direction that is downwards and parallel to the dip of a structural surface.

DOWN-HOLE GEOPHYSICAL LOGGING - the process of lowering an instrument into a borehole or well and recording continuously on a meter at the surface some physical property of the rock material being logged.

DRAG FOLDS - minor folds that form in an incompetent bed when the competent beds on either side of it move in such a way as to subject it to a couple; any fold that is a subsidiary part of a larger fold.

EARTHQUAKE INTENSITY/ACCELERATION - a measure of the effects of an earthquake at a particular place on humans and/or structures.

ENTRENCHMENT - the process of a stream eroding downward so as to form a trench.

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EPICENTER - the point on the Earth's surface which is directly above the focus of an earthquake.

EPICENTRAL INTENSITY - a measure of an earthquake's intensity at its epicenter.

EQUIDIMENSIONAL - a textural term describing a material in which all crystals or grains are essentially the same size.

ESCARPMENT - a long, more or less continuous cliff or relatively steep slope facing in one general direction, breaking the general continuity of the land by separating two level or gently sloping surfaces.

EUHEDRAL - a crystal in which the crystal faces are very distinct and characteristic of the particular mineral or element.

EUSTATIC - pertaining to worldwide changes of sea level that affect all of the oceans.

EVAPORITE - a nonclastic sedimentary rock composed primarily of minerals precipitated from a saline solution.

EXFOLIATION - the process by which thin concentric shells are successively broken loose from the bare outer surface of a large rock mass.

EXTERNAL SHEATH ZONE - a zone that forms the boundary between a spine of salt and the outside of the salt dome type of boundary shear zone.

EXTRUSION - the igneous process of emitting lava onto the Earth's surface; also, the rock so formed.

FACIES - the sum of all primary lithologic and paleontologic characteristics exhibited by a sedimentary rock and from which its origin and environment of formation may be inferred; the general aspect, nature or appearance of a sedimentary rock produced under or affected by similar conditions.

FAULT - a surface or zone of rock fracture along which there has been displacement.

FERRUGINOUS - pertaining to or containing iron.

FIRST ORDER LEVELING - spirit leveling to establish a horizontal line of sight of high precision and accuracy.

FISSILE - capable of being easily split along closely spaced planes.

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FLAGGY ROCK - rock that tends to split into layers 1 to 5 cm (0.39 to 1.96 in) in thickness.

FLEXURE - a fold formed by warping or other gentle deformation rather than by compression; c.f. hinge fault.

FLEXURE FAULT - a fault that originally occurred as a flexure.

FLUVIATILE - pertaining to river flow and river action.

FORMATION - a basic convenient unit of rocks, of considerable thickness and extent, used in mapping, describing, or interpreting the geology of a region, and the only formal classification that is used for completely dividing the whole geologic column all over the world into named units on the basis of lithology.

FORMATION PACKER - a drill-stem testing apparatus utilized in boreholes to isolate a particular zone of interest in the rock section by inflating flexible steel-meshed rubber cushions against the sides of the hole, thus permitting formation fluids to be sampled.

FRACTURE - general term for any break or separation in a rock.

FRIABILITY - the ease with which a material can be crumbled.

GEOHYDROLOGY - a term referring to the flow characteristics of subsurface waters; c.f. ground-water hydrology.

GEOID - the "figure of the Earth" considered as a sea level surface extended continuously through the continents.

GEOLOGIC OR STRATIGRAPHIC CROSS SECTIONS - a diagram that shows geologic features transected by a given plane (usually a vertical plane).

GEOLOGIC STRUCTURE - the general disposition, attitude, arrangement, or relative positions of the rock masses of a region or area; the sum total of the structural features of an area; also used to designate any physical arrangement of rocks, such as an anticline or fault, due to earth forces.

GEOMORPHOLOGY - the science that treats the general configuration of the Earth's surface and its relationship to geologic forces. The interpretative study of landforms; see physiography.

GEOPHYSICAL LOGS - a log obtained by lowering an instrument into a borehole or well, while recording continuously on a meter at the surface some physical property of the rocks through which it passes.

GEOPRESSURED - subsurface condition in which the fluid pressures exceed the normal hydrostatic pressures, due generally to the weight of the overburden.

GEOSYNCLINE - a mobile downwarping of the crust of the Earth, measured in scores of kilometers, which is subsiding as sedimentary and volcanic rocks accumulate to a thickness of thousands of meters; adj. geosynclinal.

GLACIO-ISOSTASY - the state of hydrostatic equilibrium in the Earth's crust as influenced by the weight of glacial ice.

GLAUCONITE - a dull green, amorphous, and earthy or granular mineral of the mica group.

GOUGE - a thin layer of soft rock material between a salt plug and adjacent strata created by cataclasis during diapirism.

GRABEN - an elongated, relatively depressed crustal unit or block that is bounded by faults along its sides; down-dropped fault block; c.f. horst.

GRAIN DENSITY - specific gravity of the grains composing a sediment or sedimentary rock.

GROUND WATER - that part of the subsurface water which is in the zone of saturation.

GROUP - a major rock-stratigraphic unit, next higher in rank than formation; consisting wholly of two or more contiguous or associated formations having significant lithologic features in common.

GROWTH FAULT - a fault in sedimentary rocks that forms contemporaneously and continuously with deposition.

GYPSUM - a mineral consisting of hydrous calcium sulfate: $CaSO_4 \cdot 2H_2O$.

HALITE - native salt; the mineral sodium chloride: NaCl.

HALOKINETICS - a general term for the study of the structure and mechanism of salt movements.

HALO-TECTONIC - pertaining to the forces resulting in salt movement.

HECTARE - a metric unit of land area equal to 10,000 square meters or 2.471 acres.

HEMATITE - a common iron mineral consisting of ferrous oxide: Fe_2O_3.

HIATUS - a break or interruption in the continuity of the geologic record.

HINTERLAND - an area bordering, or within, an orogenic belt on the internal side, away from the direction of overfolding and thrusting.

HOMOCLINAL SHEAR ZONES - a tabular zone of rock that has been brecciated by parallel fracture along rock units which have the same dip.

HOMOGENEOUS SEISMICITY - seismic activity equally dispersed throughout its occurrence.

HORST - an elongated, relatively uplifted crustal unit or block that is bounded by faults on its long sides; uplifted fault block.

HOST ROCK - a body of rock which includes relatively small amounts of other rocks or mineral deposits.

HYDROGEOLOGY - the science that deals with subsurface waters and related geologic aspects of surface waters.

HYDROLOGY - the science that deals with continental water, its properties, circulation, and distribution on and under the Earth's surface and in the atmosphere.

IGNEOUS - said of a rock or mineral that solidified from a molten or partially molten state, i.e. from a magma; contrasted to sedimentary.

INDURATED - condition of a compact rock or soil hardened by the action of pressure, cementation, or especially heat.

INLIER - an area or exposed group of rocks surrounded by outcrops of younger rocks.

INTENSITY RECURRENCE FUNCTION - a statistically determined relationship expressing the probabilistic likelihood of experiencing a certain [earthquake] intensity as a function of time.

INTERFLUVES - the areas between rivers; esp. the relatively undissected upland or ridge between two adjacent valleys containing streams flowing in the same general direction and belonging to the same general drainage basin or watershed.

INTERGLACIAL - pertaining to the time interval between two successive glacial epochs, or between two glacial stages.

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INTERNAL BOUNDARY ZONE - a zone which forms the boundary between two salt spines.

INUNDATED - to be covered with water; flooded.

ISOCHORE - a line drawn through equal interval between two beds or other places.

ISOCHORE MAP - a map that shows the varying interval between two designated stratigraphic planes or horizons, possibly including one or more unconformities. c.f. isopach map.

ISOCLINAL FOLDS - a fold in which the limbs have been so compressed that they have the same dip.

ISOPACH - a line drawn on a map through points of equal thickness of a designated stratigraphic unit.

ISOPACH MAP - a map that shows the thickness of a designated stratigraphic unit; c.f. isochore map.

ISOSEISMAL - a line connecting points on the Earth's surface at which earthquake intensity is the same.

ISOSTASY - the condition of equilibrium [comparable to floating] of the units of the brittle crust above the denser plastic mantle. Principle of equilibrium level between coastal segments of equal area having same mass.

ISOSTATIC (SEA LEVEL CHANGES) - changes in sea level resulting from adjustments in the Earth's crust to maintain equilibrium among units of varying mass and density.

JUVENILE WATER - term applied to water that is known to be derived directly from magma and comes from the Earth's interior to the surface for the first time.

KAOLINITE - a common, white to grayish or yellowish clay mineral of the kaolin group: $Al_2 Si_2 O_5 (OH)_4$.

KNICKPOINT - a point of abrupt change in the longitudinal profile of stream valleys.

LENS - a geologic deposit bounded by converging surfaces, thick in the middle and thinning toward the edges.

LENTIL - a minor rock stratigraphic unit of limited geographic extent, being a subdivision of a formation and similar in rank to a member, and thinning out in all directions.

GLOSSARY OF GEOLOGICAL TERMS (Continued)

LEVELING - the operation of determining the comparative altitude of different points on the Earth's surface.

LIGNITE - a brownish-black coal that is intermediate in coalification between peat and subbituminous coal.

LIMESTONE - a class of rock which is composed of at least 80 percent of calcium or magnesium carbonates.

LIMONITE - a general term for a group of brown, amorphous, naturally occurring hydrous ferric oxides not specifically identified.

LINEAMENT - an alignment of surficial features that is structurally controlled, such as stream beds, vegetation or soil or rock tone that are so controlled; commonly observed on aerial photos or topographic maps.

LINEAR - a straight or gently curved physiograhic feature on the Earth's surface.

LINEATION - a general term for any linear feature of whatever scale in a rock.

LITHOLOGY - the physical description of rocks on the basis of such characteristics as color, mineralogic composition, and grain size.

LITHOSPHERE - the solid portion of the earth, as compared with the atmosphere and hydrosphere.

LUTITE - sediment or sedimentary rock consisting principally of clay or clay-sized particles.

MARL - an old term loosely applied to a variety of materials, most of which occur as soft, loose, earthy, and semifriable or crumbling unconsolidated deposits consisting chiefly of an intimate mixture of clay and calcium carbonate in varying proportions, formed under either marine or fresh-water conditions.

MASSIFS - an embryonic salt dome rising from its source bed, still at depth.

MICRITE - a limestone with a very fine subcrystalline texture.

MODIFIED MERCALLI INTENSITY - scale (from I to XII) for evaluating earthquake shocks.

METAMORPHIC - any rock derived from preexisting rocks by mineralogical, chemical, and structural changes, essentially in the solid state, in response to marked changes in temperature, pressure, etc.

MHO - a unit of electical conductance equal to the reciprocal of ohm.

MICROFOSSIL - a fossil too small to be studied without the aid of a microscope.

MICROMHO - mho x 10^{-6}.

MICROCRYSTALLINE - said of the texture of a rock consisting of or having crystals that are small enough to be visible only under a microscope; also said of a rock having such a texture.

MICROSEISMIC MONITORING - earthquake measurement or observation by instrumental means of shocks below the sensitivity threshold of the conventional seismograph.

MINERALOGY - the study of minerals, their formation and occurrence, their properties and composition, and their classification.

NEOGENE - an informal usage for the period of time incorporating the Miocene and Pliocene of the Tertiary Period.

NERITIC - pertaining to the ocean environment or depth zone between low-tide level and 100 fathoms, or between low-tide level and approximately the edge of the continental shelf.

NONCONFORMITY - an unconformable contact between sedimentary rocks lying upon an eroded surface of older igneous or metamorphic rocks.

NORMAL FAULT - a fault in which the hanging (upper) wall appears to have moved downward relative to the footwall. The angle of the fault is usually 45-90°.

OFFLAP - the reverse of transgressive onlap, occurring where a shoreline has retreated seaward and progressively younger strata have been deposited in layers offset seaward; a type of overlap.

ONLAP - extension of successive stratigraphic units beyond the marginal limits of their predecessors onto older rocks as in the deposits of a trangressing sea; a type of overlap.

OOLITHS - one of the small, round accretionary bodies in a sedimentary rock, usually calcium carbonate.

OOLITE - a sedimentary rock usually a limestone, made up chiefly of ooliths cemented to others.

OOLITIC LIMESTONE - an even textured limestone composed almost entirely of relatively uniform calcareous ooliths.

OROGENIC BELT - a linear region that has been subjected to folding and deformation during an orogenic cycle.

OROGENY - the process by which rock structures in mountainous areas were formed.

OUTLIER - an area or group of rocks surrounded by outcrops of older rocks.

OVERBURDEN - the loose soil, silt, sand, gravel or other unconsolidated material overlying bedrock.

OVERCONSOLIDATION - consolidation resulting from desiccation or from pressure of overburden that has since been removed by erosion.

OXBOW LAKE - the crescent-shaped body of standing water situated by the side of a stream in the abandoned channel (oxbow) after the stream formed a neck cutoff and the ends of the original bend were silted up.

PALEOGENE - an informal usage for the interval of geologic time incorporating the Paleocene, Eocene, and Oligocene of the Tertiary Period.

PALEOGEOGRAPHIC MAP - a map that shows the reconstructed physical geography at a particular time in the geologic past.

PALEONTOLOGY - the study of life in past geologic periods, based on fossil plants and animals and including phylogeny, their relationships to existing plants and animals, and the chronology of the Earth's history.

PELLET - a small, usually rounded, aggregate of accretionary material; also fecal matter from fossil organisms.

PELLETAL LIMESTONE - a limestone characterized by abundant pellets.

PENCIL - long, slender pieces of rock (anhydrite) resembling pencils.

PENEPLAIN - a low, nearly featureless and gently undulating or almost-plane land surface of considerable area.

PERMEABILITY - the property or capacity of porous rock, sediment, or soil for transmitting a fluid without impairment of the structure of the medium.

PETROFABRIC - the textural features of a rock.

PETROLOGY - that branch of geology dealing with the origin, occurrence, structure and history of rocks, especially igneous and metamorphic rocks.

PETROGRAPHY - the branch of geology dealing with the description and classification of rocks, especially igneous and metamorphic rocks.

PHYSIOGRAPHY - the descriptive study of landforms; see geomorphology.

PIERCEMENT DOME - see diapir.

PIERCEMENT STAGE - a stage of salt dome development in which the salt rises vertically, penetrating the overlying strata.

PIEZOMETRIC SURFACE - see potentiometric surface.

PILLOWING - a stage of salt dome development in which the salt is said to move laterally into mounds or "pillows."

PINCH-OUT - the termination or end of a stratum, vein, or other body or rock by tapering or progressively narrowing to extinction.

PLASTICITY - the property of a material that enables it to undergo permanent deformation without appreciable volume change or elastic rebound, and without rupture.

POTASH - potassium carbonate, K_2CO_3.

POROSITY - the property of a rock, soil, or other material containing interstices, and the ratio of the volume of its interstices to its total volume.

POTENTIOMETRIC SURFACE - an imaginary surface representing the static head of ground water and defined by the level to which water will rise in a well; c.f. piezometric surface.

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PRODELTA - that part of the delta that is below the effective depth of wave erosion, lying beyond one delta front and sloping gently down to the floor of one basin into which the delta is advancing.

PROLATE - designating the shape of a solid, especially of a spheroid having its polar axis longer than its equatorial diameter; cigar-shaped.

QUAQUAVERSAL DIP - dipping outward in all directions from a central point, as a dome in stratified rocks.

RADIONUCLIDE - a radioactive species of atom characterized by the number of neutrons and protons in its nucleus; a product of radioactivity.

REDBEDS - sedimentary strata composed largely of clastic materials that are predominantly red in color due to the presence of hematite.

RELICT - a relief feature or rock remaining after other parts have disappeard.

REMOTE SENSING - in a restricted sense the practice of data collection in the wavelengths from ultraviolet to radio regions; a practical outgrowth of airborne photography.

RESIDUAL GRAVITY - the difference between theoretical, calculated, and observed terrestrial gravity, measured in milligals.

RESISTIVITY - the resistance to electrical current of a rock unit, measured instrumentally as a reconnaissance method of determining the nature of rocks in the shallow subsurface.

RIFT - a narrow cleft, fissure, or other opening in rock made by cracking or splitting; a large strike-slip fault parallel to regional structures.

RIFT BASIN - a deep central cleft in the crest of a mid-oceanic ridge.

RIFT VALLEY - valley produced by subsidence of a block bounded by two rifts.

RIM SYNCLINES - downfolds that tend to develop around the periphery of salt domes due to sagging of the overlying strata into a circular void created by the removal of salt from the source strata.

SALINE - a natural deposit of common salt or of any other soluble salt, e.g., an evaporite; pertaining to, consisting of, or containing salt; refers also to various features related to a natural evaporitic environment, e.g., playa, salt lake, salt pan, etc.

SALT CORE - a cylindrical sample of salt obtained by drilling into a rock salt body with a hollow drill bit; also, the central portion of salt stock.

SALT DOME - a structure resulting from the upward movement of a salt mass.

SALT STOCK - the salt mass portion of a salt dome structure.

SANDSTONE - a cemented or otherwise compacted detrital sediment composed predominantly of quartz grains.

SEDIMENTARY ROCK - a rock resulting from the consolidation of loose sediment that has accumulated in layers.

SEISMIC - pertaining to an earthquake or Earth vibration, including those that are artificially produced.

SEISMICITY - the phenomenon of Earth movements.

SEISMIC REFLECTION - a geophysical technique which measures the time of energy from a seismic source which has been reflected.

SEISMIC SURVEY - the gathering of data from artificially induced vibrations.

SEISMOLOGY - the study of earthquakes; by extending the study of the structure of the interior of the Earth via both natural and artificially generated seismic signals.

SEISMOTECTONIC REGION - a region characterized by a relative consistency of historical seismicity and of structural activity among geologic features contained therein.

SERIES - a time-stratigraphic unit generally classed next in rank below a system, and above a stage, properly based on a clearly designated stratigraphic interval in a type area.

SHEAR - strain resulting from compressive stresses that cause or tend to cause contiguous parts of a body to slide relative to each other in a direction parallel to their plane of contact; usually at an angle other than perpendicular to the direction of stress.

SHALE - a laminated sediment in which the constituent particles are predominantly of the clay grade.

SHEAR MODULUS/S-WAVE VELOCITY -rigidity or shear modulus is a measure of the stress-strain ratio for a simple shear.

SHEAR WAVES - that type of seismic body wave which is propagated by a shearing motion of material so that there is oscillation perpendicular to the direction of propagation.

SHEATH (Lighology)- rock material, commonly shale, which surrounds or encompasses a salt plug.

SHEATH (Struct.)- pertaining to the external zone of a salt stock in which expansion of the salt has taken place, increasing the porosity and permeability.

SIDERITE - a rhombohedral mineral: $FeCO_3$.

SIDETRACKING - the practice of diverting multiple subsurface drill-holes from a single surface drill-hole.

SINKHOLE - a general term for a depression in an area of karst topography that is formed either by the solution of the surficial limestone or by the collapse of underlying caves.

SLABBING/SPALLING (OF WALLS) - the natural process of sloughing of large slabs of salt from the walls of mine workings.

SLOPE STABILITY - the quality of permanence or resistance of a natural or artificial slope to failure by landsliding.

SOLUTION - a process of chemical weathering by which rock material passes into solution.

SONIC LOG - an acoustic log continuously recording travel time of sound from the surface to an instrument lowered down a borehole.

SPALLING - see slabbing/spalling.

SPINE - a vertical protrusion of a salt stock which may or may not move upward at a different rate than the rest of the stock.

STACKING - a statistical method of processing seismic records that has the effect of averaging the intensity of the rays of energy from a single reflection point, while reducing the relative amount of noise or signal interference.

STALACTITE - a cylindrical or conical deposit of minerals hanging from the roof of a cavern.

STALAGMITE - a column or ridge of material rising from the floor of a cavern or mine, caused by water dripping down from above.

STRADDLE-PACKER - a drill-stem testing apparatus utilized in boreholes to isolate a zone or interval of interest in the rock section (see formation packer).

STRATIGRAPHY - the arrangement of strata especially as to geographic position and chronological order of sequence: the branch of geology that deals with the description of minor and major divisions of rock.

STRATUM - a tabular or sheet-like mass, or a single and distinct layer, of monogeneous or gradational sedimentary material, distinguishable from mass above and below.

STREAM REACH - arbitrary lengthwise section of a stream.

STRIKE - the direction or trend of a structural surface with the horizontal plane.

STRUCTURAL GEOLOGY - that branch of geology that deals with the form, arrangement, and internal structure of the rocks.

STRUCTURE - the general disposition, attitude, arrangement, or relative positions of the rock masses of a region or area.

SUBAERIALLY - occurring beneath the atmosphere or in the open air; esp. said of conditions and processes (such as erosion) that exist or operate on or immediately adjacent to the land surface; c.f. - subaqueous.

SUBHEDRAL - a crystal in which the crystal faces are intermediate between distinct and non-distinct.

SYLVITE - a white or colorless isometric mineral, potassium chloride (KCl). It is the principal ore of potassium.

SYNCLINE - a fold, the core of which contains the stratigraphically younger rocks; it is concave upward.

SYNTHETIC SEISMOGRAM - artificial seismogram produced by computer from the acoustic velocity log of a well.

TARRY OIL SEEP - a place of emergence of tar-like petroleum as a result of the slow migration from its buried source, through minute pores or fissures.

TECTONIC - dealing with the rock structure and external forms resulting from the deformation of the earth's crust; as applied to earthquakes it is used to describe shocks not due to volcanic action or the collapse of caverns or landslides.

TECTONIC STRUCTURE - a large scale dislocation in or distortion of the Earth's crust.

TERRACE - any long, narrow, relatively level, or coastward gently inclined surface bounded on one edge by a steeper descending slope and also along the other by a steeper ascending slope; a large bench or step-like ledge.

TERRIGENOUS - produced from or of the Earth, terrigenous deposits are sediments derived from the land and deposited in shallow marine area.

TERRESTRIAL - pertaining to the land surface of the earth; terrestrial deposits are those made on land, above tidal reach.

THROW - on a fault, the amount of vertical displacement.

TILT - the angle at the perspective center between the plumb line and the perpendicular from the interior perspective center to the plane of a photograph.

TILTMETER - an instrument that measures slight changes in tilt of the Earth's surface.

TUFF - a compacted pyroclastic deposit of volcanic ash and dust that may contain up to 50% sediments such as sand or clay.

TUFFACEOUS MATERIAL - sediment containing up to 50% tuff.

UNCONFORMABLE - strata or stratification exhibiting the relation of unconformity to the older underlying rocks.

UNCONFORMITY - a substantial break or gap in the geologic record where a rock unit is overlain by another that is not next in stratigraphic succession.

UPDIP REGION - a direction which is upwards and parallel to the dip of a structure or surface.

UPLIFT - a structurally high area in the crust produced by positive movements that raise or upthrust the rocks.

VALES - a rift valley or tectonic valley; also land between two parallel cuestas.

GLOSSARY OF GEOLOGICAL TERMS (Continued)

VIRGIN ROCK - fresh rock that has not been weathered.

VOID RATIO - the ratio of the volume of void space to the volume of solid substance in any material consisting of voids and solid material.

VUG - a cavity, often with a mineral lining of different composition from that of the surrounding rock.

WATERSHED - the area contained within a drainage divide above a specified point on a stream.

WOLD - a range of hills produced from differential erosion from inclined sedimentary rocks; a cuesta.

XENOLITH - rock fragments contained in an igneous body of rock which are foreign to the host rock; inclusion.

CONVERSION FACTORS

The conversion factors used in this report are based on the following table. In most instances, the metric-to-standard measurement conversions represent rounded-off figures in this report.

To convert from	To	Multiply by
millimeter (mm)	inch (in)	0.03937
meter (m)	foot (ft)	3.281
kilometer (km)	mile (mi)	0.6214
meter^2 (m^2)	foot^2 (ft^2)	10.76
kilometer^2 (km^2)	mile^2 (mi^2)	0.3861
hectare (-)	acre (-)	2.471
kilogram (kg)	pound (lb)	2.205
tonne (-)	ton (-)	0.893
liter (l)	gallon (gal)	0.2642
kilometers^3 (km^3)	miles^3 (mi^3)	0.244
kilopascal (kPa)	atmosphere (atm)	0.009869
milligrams per liter (mg/l)	parts per million (ppm)	1.0
liter per second (l/sec)	gallon per minute (gal/min)	15.85

ABBREVIATIONS AND ACRONYMS

AEC	Atomic Energy Commission
BEG	Texas Bureau of Economic Geology
BMI	Battelle Memorial Institute
BNI	Bechtel National, Inc.
DOE	Department of Energy
ERTS	Earth Resources Technology Satellite
FEA	Federal Energy Administration
LANDSAT	Earth Resources Technology Satellite (formerly ERTS)
LETCo	Law Engineering Testing Company
LSU/IES	Louisiana State University/Institute for Environmental Studies
MGAI	Mellen Geological Associates, Inc.
MM	Modified Mercalli
MMI	Modified Mercalli Intensity
MSGS	Mississippi State Geological Survey
MSL	Mean Sea Level
NAS	National Academy of Science
NRC	Nuclear Regulatory Commission
NSAI	Netherland, Sewell and Associates, Incorporated
NWTS	National Waste Terminal Storge
ONWI	Office of Nuclear Waste Isolation of Battelle Memorial Institute
ORNL	Oak Ridge National Laboratories
OWI	Office of Waste Isolation/Union Carbide Corp.
SCS	Soil Conservation Service
TAB	Technical Advisory Board
TNRIS	Texas Natural Resource Information System
USGS	United State Geological Survey
USM	University of Southern Mississippi

1 INTRODUCTION

This report has been prepared by Law Engineering Testing Company (LETCo) for the Office of Nuclear Waste Isolation (ONWI) to present the results of the Area Characterization phase of the Gulf Coast Salt Domes (GCSD) Project. The project, begun in 1977, entailed collection and analysis of geologic and hydrologic data to determine if salt domes, as natural structures, are adaptable for use as protective repositories for the terminal storage of radioactive wastes. In addition, if salt domes are found to be generally favorable, research for this project will be directed toward development and analysis of data to provide a basis for the ultimate selection of one or more salt domes which would be the prototype(s) of a completely serviceable nuclear waste repository. This report is neither a hazard analysis nor a safety report, though it can be useful input to such documents if a Gulf Coast salt dome is chosen as a repository site for nuclear wastes.

To meet the objectives discussed above, investigations and analyses have been made to determine the tectonic environment, geometry, geologic characteristics, surface characteristics and surface and subsurface hydrologic conditions at seven specific dome sites and their surrounding areas (Figure 1-1). Most geologic authorities agree that the domes of the Interior Salt Basins are stable. They believe that the interior domes began to develop about 200 million years ago and, following emplacement and cessation of movement, they have remained quiescent for at

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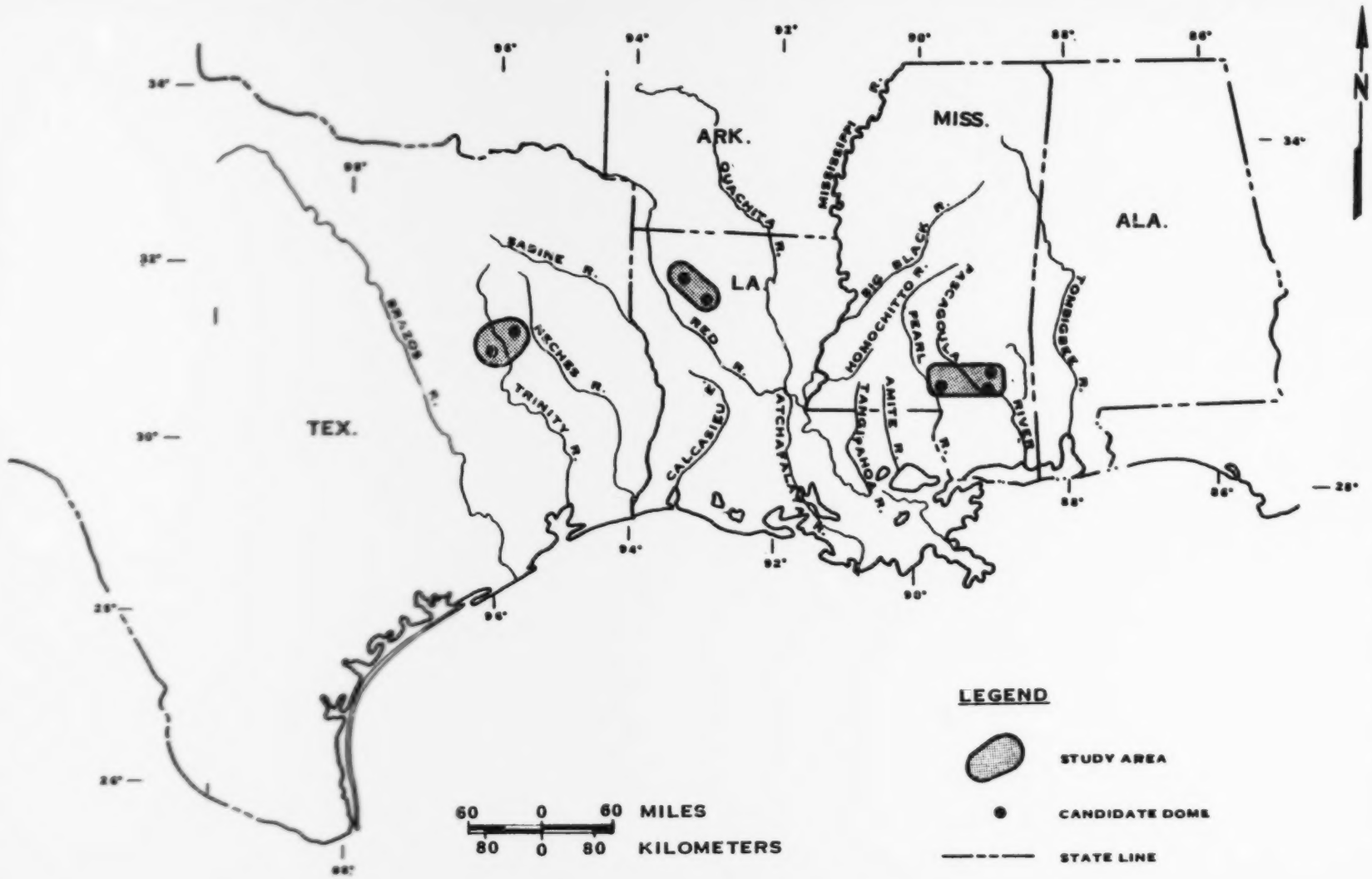

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T-1397-1

NATIONAL WASTE TERMINAL STORAGE PROGRAM
GEOLOGIC EVALUATION GULF COAST SALT DOMES
LAW ENGINEERING TESTING COMPANY
MARIETTA, GEORGIA

LOCATION MAP OF STUDY AREAS AND CANDIDATE DOMES

JOB NO. MV9600 FIGURE 1-1

FIGURE 1-1

2

least the past 2 million years. By studying the tectonic environment, it is possible to test this hypothesis of dome stability by establishing the growth history of the domes and comparing the conditions which precipitated movement in the past to conditions which exist presently and which are expected to exist in the future. The tectonic stability study was also necessary to make an inventory of the major structures in the region and to evaluate the effect that they might have on the long-term stability and shape of the domes.

The area available for development of a repository was determined through an investigation of salt dome geometry. The size, shape, depth, and exact location of each salt stock, as well as the thickness and location of the overlying caprock, were determined through modeling based on well information, gravity surveys, and seismic surveys.

The geologic aspects of each dome and surrounding area were investigated to provide knowledge of each dome's physical characteristics. These characteristics affect the design, safety, and economics of repository development. Models of each dome were used to establish domal relationships to the surrounding geologic formations which were penetrated, and to which the domes have become physically adjusted. It was also important to determine if any significant mineral resources existed near the domes which might be exploited during the life of a repository.

A study of surface characteristics and surface hydrology was conducted to determine the spatial arrangement, surface materials, and area available for surface facilities at each dome. The

surface hydrology was also evaluated for the long-term possibilities of flooding, erosion, and sea level changes.

The subsurface hydrology phase of this project was designed to establish patterns of ground-water circulation around the domes and generally within the Gulf Coastal Province. Fresh and saline aquifers were to be identified, and values of porosity and permeability were calculated to determine the flow paths and rates of movement away from each dome and to detect any solution activity at the domes.

The scope of Area Characterization included the collation of preexisting data to meet the objectives discussed above. These data were compiled and analyzed, then appropriate recommendations were made for field work to develop supplementary data. Approved field investigations were initiated and the resulting data were analyzed and merged with the preexisting data to amplify the data base and relevant interpretations. Portions of the investigation requiring specialized technical expertise were conducted by the LETCo Technical Advisory Board (TAB) and major technical consultants. The TAB includes the following members:

Dr. C. O. Durham	- Technical Director and Chairman, Technical Advisory Board
Dr. Saul Aronow	- Geomorphology
Dr. H. James Dorman	- Seismicity
Mr. Eugene F. Green, Jr.	- Geophysics
Mr. D. E. Hart	- Mining
Dr. Donald H. Kupfer	- Structural Geology
Dr. Frank L. Parker	- Hydrology

Professor George F. Sowers	- Remote Sensing and Geotechnical Engineering
Dr. Charles E. Weaver	- Mineralogy and Petrology

The major technical consultants contributing to the Area Characterization studies include:

Mr. Robert P. Alger	- Down-hole Geophysical Logging
Dr. E. G. Anderson	- Louisiana Geology
Dr. Ralph Kehle	- Structural Geology
Mr. Frederic F. Mellen	- Mississippi Geology
Dr. John M. Sharp	- Hydrogeology
Dr. William R. Muehlberger	- Structural Geology
Dr. Grover E. Murray	- Mineral Resources and Gulf Coast Geology
Dr. Oscar L. Paulson	- Mississippi Geology
Professor Robert W. Rodgers	- Texas Geology
Dr. Roy A. Welch	- Remote Sensing
Dr. Timothy Leland Long	- Seismicity

Also contributing to the Area Characterization studies were Louisiana State University Institute for Environmental Studies LSU/IES), the Texas Bureau of Economic Geology (BEG), the University of Southern Mississippi, and the U.S. Geological Survey (USGS). The result of data collection and analysis and the reports prepared by the TAB, LETCo technical consultants, and the contributing organizations have been assimilated into the Area Characterization report.

The Area Characterization report is divided into seven volumes. Volume I - Introduction, Background, and Summary explains the scope of the investigation, presents generic analyses applicable to the basins of the Gulf Coast Region, and summarizes the results of the Area Characterization phase. Volumes II and III - East Texas Study Area and Appendix characterize the geologic and hydrologic conditions in that part of the East Texas (Tyler) Basin defined as the East Texas Study Area, and in areas around Oakwood and Keechi Salt Domes. Volumes IV and V - North Louisiana Study Area and Appendix characterize the geologic and hydrologic conditions in the portion of the North Louisiana Salt Basin defined as the North Louisiana Study Area, and in areas around Rayburn's and Vacherie Salt Domes. Volumes VI and VII - Mississippi Study Area and Appendix characterize the geologic and hydrologic conditions of the portion of the Mississippi Salt Basin defined as the Mississippi Study Area, as well as areas around Cypress Creek, Richton, and Lampton Salt Domes.

During Area Characterization, geology, hydrology, and physical characteristics of salt domes were investigated as they relate to potential hazards of repository development. The geologic study consisted of an analysis of the structure, stratigraphy and mineral resources of the region, study areas, and domal areas. The hydrologic study investigated water chemistry, aquifers, flow paths, hydraulic characteristics, and the relationship between surface and subsurface water systems. Growth rates and internal structure of salt domes, as well as the geometry of the candidate domes, were studied in order to

characterize the salt domes of the Gulf Coast thoroughly. Potential hazards to repository development, including earthquakes, floods, and erosion, were also studied.

It is important to point out that the ability to predict the occurrence of natural hazards varies with the hazard itself and with the length of observation time involved. For example, because it is possible to monitor a sequence of events, sea level changes, climatic changes, and erosion can be predicted fairly accurately in the near term, but with less accuracy in the far term. Tectonic movements and floods are random events which are difficult to predict with accuracy. Therefore, postulations of extreme conditions of inundation or denudation are exercises to determine a range of conservative, unlikely possibilities rather than a dependable evaluation of eventualities.

1.1 PREVIOUS EVALUATIONS OF GULF COAST SALT DOMES

1.1.1 EVALUATION OF SALT AS A STORAGE MEDIUM: In 1954 the U.S. Atomic Energy Commission (AEC) approached the National Research Council (NRC) and the National Academy of Science (NAS) for a possible solution to the radioactive waste disposal problem (Hess and others, 1957). A conference of geologists, marine scientists, and oceanographers was held at Woods Hole Oceanographic Institute in Massachusetts late in 1954 to consider a proposal to dump radioactive waste in the ocean and to select the most appropriate sites for such disposal. Because of potential hazards to marine life, the corrosive properties of sea water over long periods of

time and the unsettled international problem of jurisdiction over the deeper ocean basins, it was strongly recommended that a disposal system on land be developed (Atomic Energy Commission, 1955).

In 1955 the NAS and NRC appointed a Steering Committee for Radioactive Waste Disposal which sponsored a conference of leading geophysicists, geologists, and nuclear industry scientists to consider methods and areas suitable for land disposal. This conference concluded that the most promising place for disposal was in rock salt formations. This position has since been reaffirmed by NAS and NRC. The superiority of salt over other rock types (Hess and others, 1957) is derived from a number of characteristics and properties, including:

(1) Abundance -- Large areas of the continental United States are underlain by thick beds and domes of fairly pure salt at reasonable depths.
(2) Structural strength -- The temporary compressive strength of rock salt approaches that of concrete.
(3) Radiation protection -- Salt has fairly good radiation shielding properties.
(4) Mineability -- Salt is relatively easy to mine.
(5) Accessibility -- Many inactive or abandoned salt mines are available for study in the United States.
(6) Thermal properties -- Salt has good thermal properties; for example, its ability to conduct heat is generally better than that of other rock types.

(7) Inherent plasticity -- Salt has a tendency to flow and recrystallize rather than to fracture.

(8) Permeability -- Salt is relatively impermeable.

(9) Seismicity -- Salt deposits are located in areas which are relatively inactive seismically.

(10) Consistency -- Salt masses tend to be homogeneous.

1.1.2 PREVIOUS SALT MINE DISPOSAL TESTS AND RESEARCH: In order to evaluate the feasibility of disposing of solidified high-level radioactive wastes in underground salt mines, laboratory tests were conducted at Oak Ridge National Laboratories (ORNL) and in a salt mine in Permian bedded salt at Hutchinson, Kansas. A demonstration facility was subsequently developed in a salt mine in bedded salt at Lyons, Kansas. This program was designated "Project Salt Vault" and had the following major objectives:

(1) To demonstrate the techniques and equipment for handling waste containers in an underground environment

(2) To determine physical behavior of rock salt at elevated temperatures

(3) To evaluate the behavior of stainless steel and carbon steel containers in contact with salt at elevated temperatures and in the presence of moisture

(4) To evaluate the stability of rock salt under the combined effects of heat and radiation.

An evaluation of Project Salt Vault by Bradshaw and McClain (1971) concluded that all the major objectives had been met. They stated that "Most of the major technical problems pertinent to

the disposal of highly radioactive wastes in salt have been resolved..." The Lyons, Kansas site was not developed as a permanent disposal facility because of the presence of several boreholes which had not been plugged and a solution mining operation in the area.

Several countries have recognized the advantageous physical and geological properties of rock salt. A facility for disposal of low- and intermediate-level radioactive waste has been developed in an abandoned salt mine in Asse, Germany (Kuhn, 1974) and a research and development program for high-level radioactive waste is being conducted in the same mine. In addition, the Germans have proposed a facility for high-level waste disposal in salt at Gorleben. The French, Russians, and Dutch are also considering salt mines as waste repositories.

1.1.3 RECENT STUDIES: The geology and hydrology of the salt domes of the Gulf Coast Region was summarized by Anderson and others (1973) and their suitability for containment of radioactive wastes was discussed. In that report, of the 263 known or suspected on-shore salt domes in the Gulf Coastal Province, 36 were designated as potential repository sites. The criteria utilized to eliminate certain domes from consideration included (1) excessive depth to the salt (less than 600 meters (2,000 ft) was thought desirable), and (2) use by industry for gas storage or the production of oil, gas, salt, brine, or sulfur. These criteria, which are similar to those developed for potential repository sites in bedded salt, were adopted by the National Waste

Terminal Storage Program in consultation with personnel of the Oak Ridge National Laboratory.

An overall review of the concept of radioactive waste disposal by burial in salt domes was published by Ledbetter and others (1975). They concluded that there is no valid technical or geological reason for prohibiting the use of salt domes as repository sites for high-level radioactive waste. They stated that the salt domes in the Interior Salt Basins are tectonically stable, and suggested that, if a dome is surrounded by shale and lies below the base of actively circulating, fresh ground water, it would also be hydrologically stable. They described the characteristics of a theoretical dome which would be ideal for a radioactive waste repository and recommended further consideration of particular salt domes which they felt met this description.

An investigation of the salt domes in the Mississippi Salt Basin was conducted by Mellen Geological Associates, Inc. (MGAI) of Jackson, Mississippi (Mellen, 1976). MGAI investigated 47 known and 3 suspected salt domes which rise to within 1,524 meters (5,000 ft) of the surface in southern Mississippi.

LSU/IES began a continuing study of the Gulf Coast salt domes in the spring of 1974. Of the current cooperating agencies, LSU/IES has been involved for the longest time. The initial LSU/IES report of June, 1975 stated three specific goals: "(1) to evaluate the relative degree of stability of domes within the interior province, and to develop the feasibility of more precise methods of evaluation; (2) to assess the hydrologic stability of domes within the interior province; and, (3) to establish a

preliminary basis for obtaining precise measurements of the sizes and shapes of some key domes through the use of geophysical and other data." The LSU/IES team has continued to perform studies oriented to these goals at Vacherie and Rayburn's Domes and has not taken a role in the evaluation, ranking, and selection of specific domes for development as repositories. This group has recorded findings in a series of annual reports (Martinez and others, 1975, 1976, 1977, 1978, 1979, and 1980).

BEG began its investigations of the East Texas Salt Basin in January, 1978. The Bureau has compiled substantial generalized information on the East Texas Salt Dome Basin and more detailed site-specific information on a number of salt domes in east Texas. BEG has not restricted its work to the three Texas domes considered as repository candidates. The present work plan includes "regional and generic tasks to be undertaken concurrently with local studies more specifically applicable to area characterization of certain salt domes." BEG has actively participated in program planning and selection of test sites.

USGS has been involved in geohydrologic studies to varying degrees in the various states. A progress report of studies of the geohydrology of the North Louisiana Salt Basin based on existing data was prepared by the USGS in 1978 (Hosman, 1978). In Mississippi, the USGS has participated in program planning and selection of test sites. A preliminary report of the geohydrology of the Mississippi Salt Basin was published by USGS (Spiers and Gandl, 1980). In Texas, USGS has evaluated the geohydrology of selected salt domes (USGS, 1980a), and has published water quality data relevant to salt domes (USGS, 1980b).

In 1976 the National Waste Terminal Storage Program (NWTS) was created with the goal of providing radioactive waste repositories in deep geologic formations in various parts of the country. The purpose of the NWTS program is to safely dispose of, or to store in isolation for an indefinite period of time, radioactive waste from commercial nuclear reactors. NWTS is now being administered for the Department of Energy (DOE) by the Office of Nuclear Waste Isolation, Battelle Memorial Institute at Columbus, Ohio. The NWTS program was originally administered by the Office of Waste Isolation of Union Carbide Corporation. In June of 1977, when the U.S. Energy Research and Development Administration, which had originally contracted with Union Carbide to manage the NWTS program, was absorbed by the newly created U.S. Department of Energy, the responsibilities of Union Carbide were transferred to Battelle Memorial Institute.

An objective of the NWTS Program is to locate a repository in a suitable medium. If salt domes are determined to be suitable, one must be chosen that does not have significant associated petroleum reserves in order (1) to avoid later exploratory drilling in the vicinity of the facility, and (2) to avoid denying valuable reserves to posterity. The petroleum engineering consulting firm of Netherland, Sewell and Associates, Inc. (NSAI) was retained to study the present and possible future oil and gas development of areas immediately surrounding the Interior Salt Basins (Netherland, Sewell, and Associates, 1975). NSAI and the Office of Waste Isolation of Union Carbide Corporation selected

25 of the interior "unrejected domes" recommended by Anderson and others (1973) for compilation of available literature.

In 1977, LETCo was selected as the Geologic Project Manager for the Gulf Coast Salt Domes Project by Union Carbide Corporation, and later continued in this capacity with Battelle Memorial Institute. LETCo's primary responsibility was to coordinate all study activities and data acquisition for the salt domes project.

1.2 PROGRAM PHASES

The planned three-stage approach to the ultimate selection of a repository site is to investigate successively smaller areas and evaluate them with respect to acceptance criteria. In the Gulf Interior Region three stages of increasingly concentrated investigation and evaluation are designated Regional Characterization studies, Area Characterization studies, and Location and Site Characterization studies.

The completed Regional Characterization studies were designed to characterize the entire Gulf Interior Region and to select areas within the region for the more detailed Area Characterization studies reported herein. Three areas, encompassing eight domes of interest, were identified during the Regional Characterization studies for further study in the Area Characterization phase.

Following completion of the Area Characterization studies, a comprehensive Geologic Site Characterization Plan will be developed. The Geologic Site Characterization Plan will be developed as a cooperative effort of appropriate technical experts, the

respective state institutional agencies, the USGS, LETCo and its Technical Advisory Board, and ONWI with the Geologic Review Group. This plan will review and evaluate Area Characterization investigative methods, findings, and conclusions, and will consider additional research methods applicable to dome specific studies.

1.2.1 SCOPE OF AREA CHARACTERIZATION: The recommendation of the previous phase of this project, Regional Characterization, was to perform a limited investigation during the Area Characterization phase to obtain additional field data near the following study domes and their surrounding areas (Figures 1-2, 1-3 and 1-4):

Keechi Dome, Texas
Oakwood Dome, Texas
Palestine Dome, Texas
Rayburn's Dome, Louisiana
Vacherie Dome, Louisiana
Cypress Creek Dome, Mississippi
Lampton Dome, Mississippi
Richton Dome, Mississippi.

Palestine Dome was eliminated early in the study because of collapse features caused by dissolution of the salt stock associated with past brining operations.

The goal of the Area Characterization study was to conduct sufficient investigations of certain key technical items, which would enable the Geologic Project Manager to recommend to ONWI three or four candidate salt domes to be studied in substantial detail during the Site Characterization phase.

An Area Characterization Technical Program Plan was developed to support the National Waste Terminal Storage Site Performance

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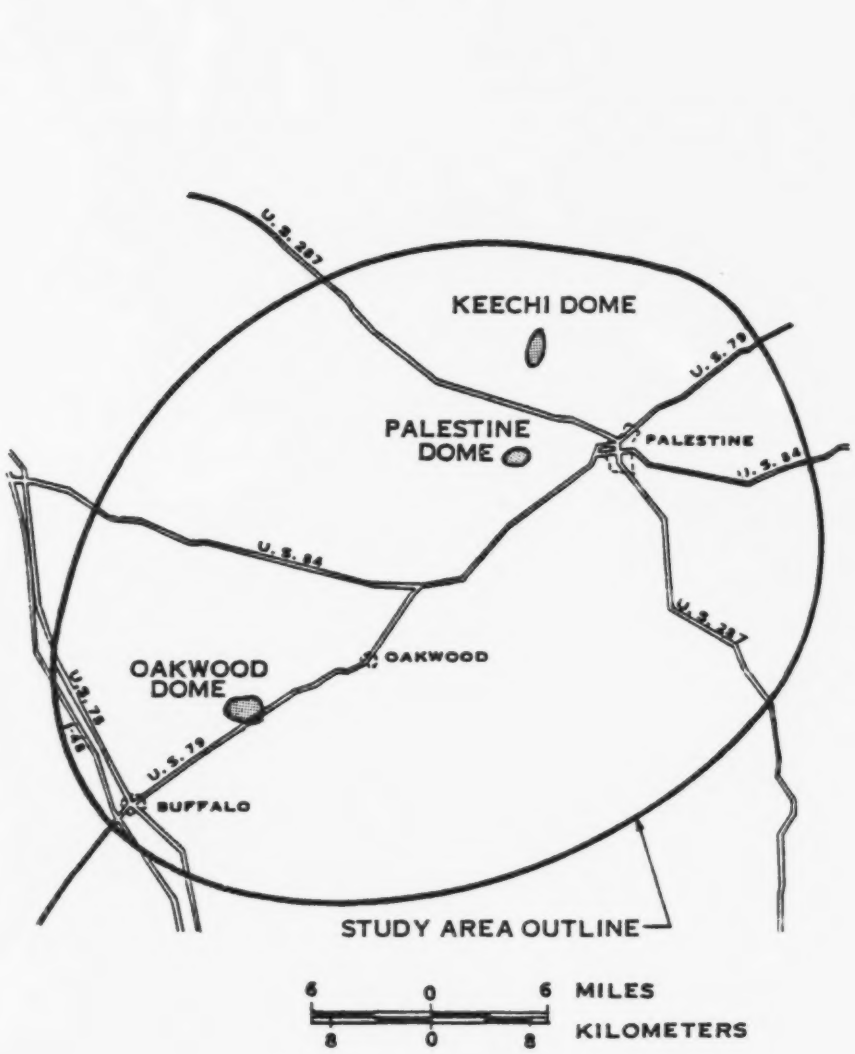
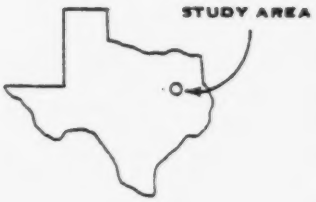


LEGEND

AREA OF SALT DOME AT ELEVATION -3000 FEET MSL.



PREPARED ____ DATE ____ REVISED ____ DATE ____ REVISED ____ DATE ____ APPROVED ____ DATE ____ T-1173-1	NATIONAL WASTE TERMINAL STORAGE PROGRAM GEOLOGIC EVALUATION GULF COAST SALT DOMES LAW ENGINEERING TESTING COMPANY MARIETTA, GEORGIA	EAST TEXAS STUDY AREA LOCATION OF CANDIDATE DOMES JOB NO. MV9600 FIGURE 1-2

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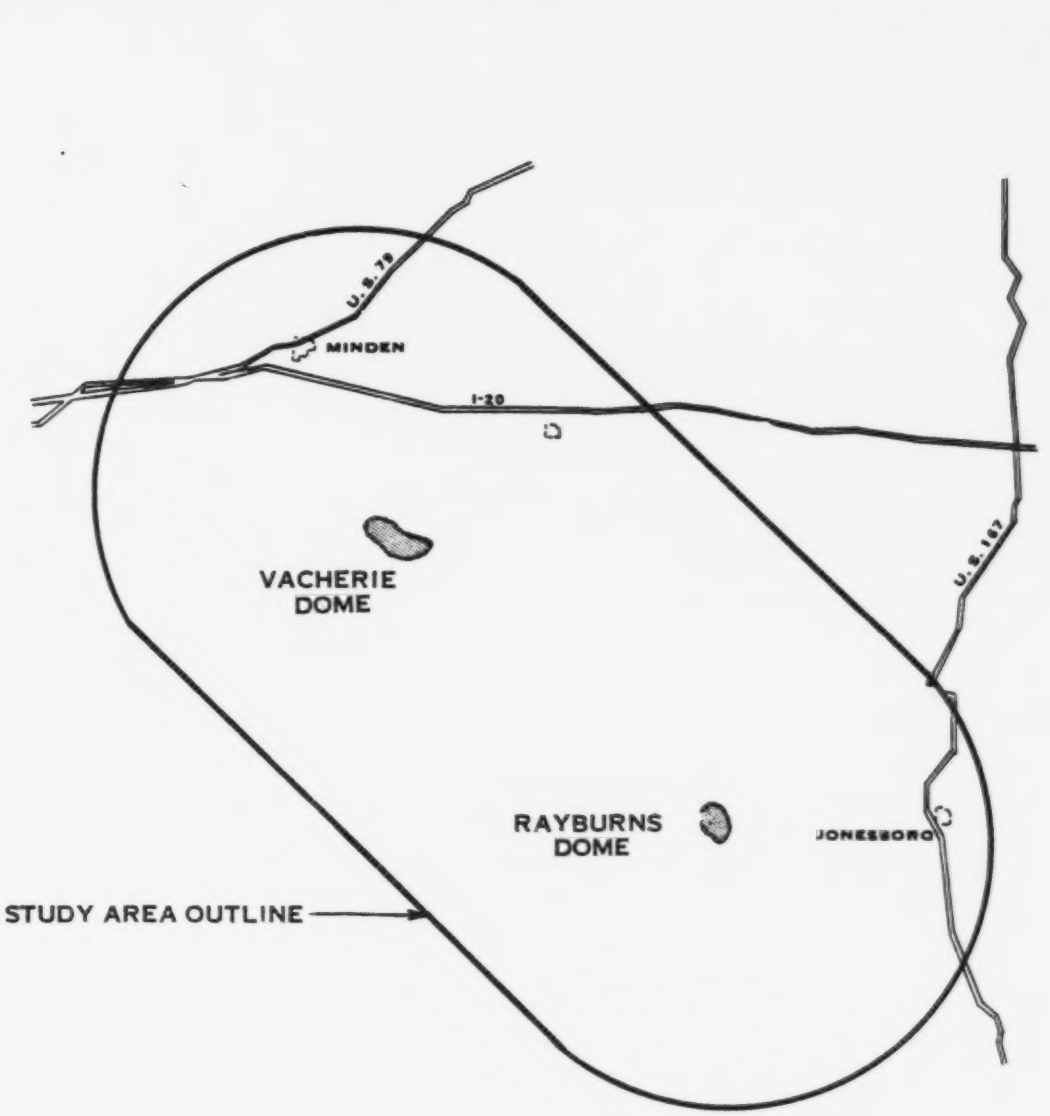

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NATIONAL WASTE TERMINAL STORAGE PROGRAM
GEOLOGIC EVALUATION GULF COAST SALT DOMES

LAW ENGINEERING TESTING COMPANY
MARIETTA GEORGIA

NORTH LOUISIANA STUDY AREA

LOCATION OF CANDIDATE DOMES

JOB NO. MV9680.51 FIGURE 1-3

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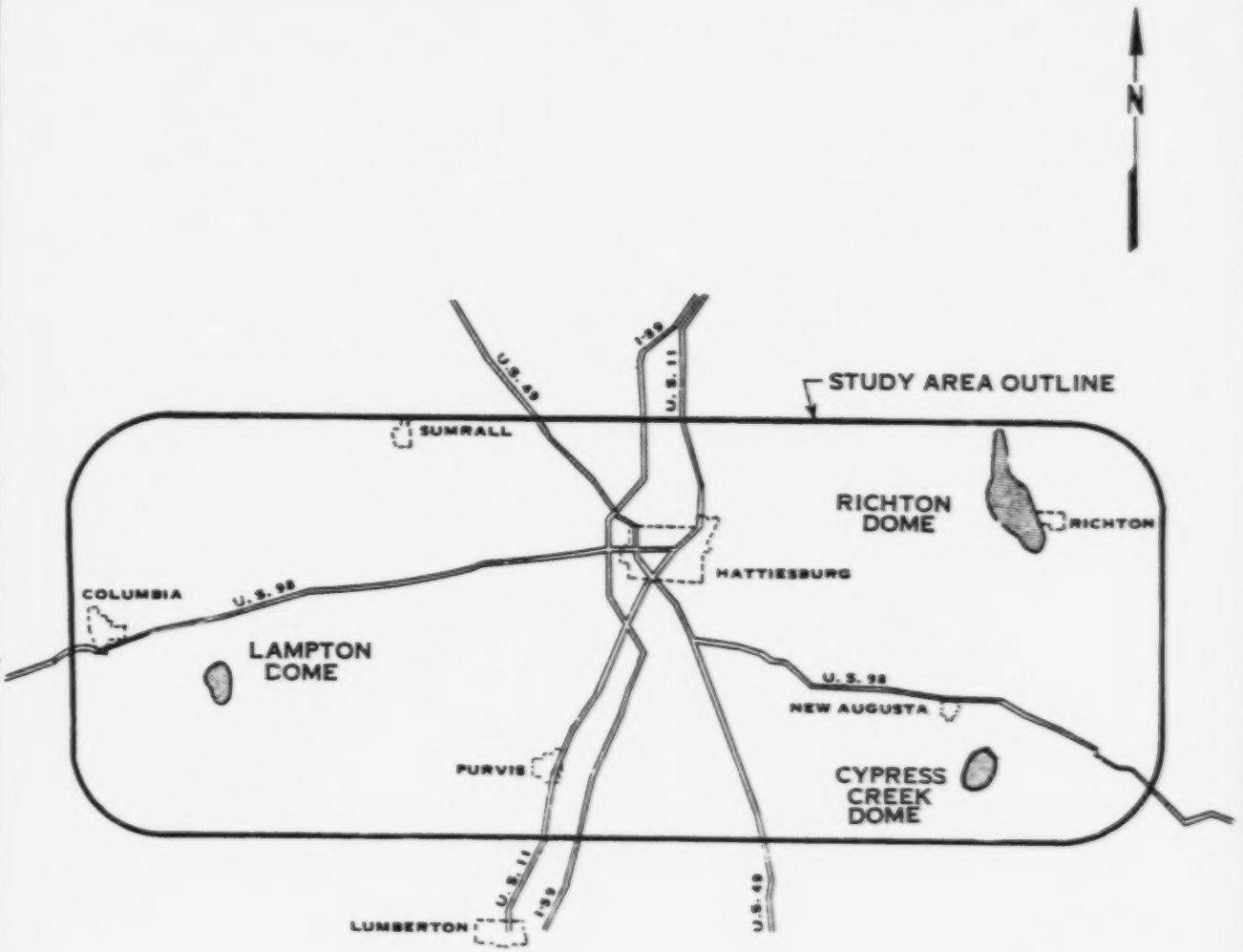

LEGEND

AREA OF SALT DOME AT ELEVATION -3000 FEET MSL

PREPARED [illegible] DATE 2-16-82	NATIONAL WASTE TERMINAL STORAGE PROGRAM GEOLOGIC EVALUATION GULF COAST SALT DOMES LAW ENGINEERING TESTING COMPANY MARIETTA GEORGIA	MISSISSIPPI STUDY AREA LOCATION OF CANDIDATE DOMES
REVISED ____ DATE ____		
REVISED ____ DATE ____		
APPROVED [illegible] DATE 2/16/82		
T-1175-1		JOB NO. MV9600 FIGURE 1-4

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Criteria for the Geologic Disposal of Nuclear Wastes [DOE/NWTS-33(2)]. These criteria consist of site geometry, geohydrology, geochemistry, geologic characteristics, tectonic environment, human resources, and surface characteristics.

Sections 2.2 and 2.3 of the proposed Preliminary Safety Analysis report outline was used as a guide in determining data acquisition and evaluation (NUS Corporation, 1978). The details of data and evaluation that will ultimately be required may change; however, it is likely that the requirements of Sections 2.2 and 2.3 will be the minimal stipulations, and that any program changes will be additions rather than alterations. The relationships between the Area Characterization Work Plan and the eventual licensing requirements are shown in Table 1-1.

1.2.2 DATA SOURCES AND ANALYSES: Numerous data sources and analysis techniques were used to characterize the geology of the study area and the near-dome areas. Initially, an extensive search of published literature was conducted to form a broad data base and to help identify areas requiring further detailed investigation. Literature sources included academic reports and theses, professional papers, and published information from federal and state agencies.

A substantial part of the preexisting data for Texas was provided by the BEG. In Louisiana, reports by the LSU/IES were a useful source of data. In addition, LETCo interviewed practicing professionals, governmental agencies, and organizations with in-depth knowledge of both regional and local geologic conditions.

Table 1-1. Relationship Between Area Characterization Report and Licensing Requirements

Area Characterization	Licensing Requirements
Geology of the Study Area (Sections 6.0, 9.0, and 12.0)[1] This will provide additional information for primary salt dome selected for a repository.	Regional Geology (Part Section 2.1)[2] Partly completed but will require details and updating for primary salt dome.
Area Mineral Resources (Sections 6.3, 9.3, and 12.3) This will provide additional details for primary salt dome.	
Near Salt Dome Geology (Sections 7.1, 10.1, and 13.1) This will provide preliminary data and report for primary salt dome.	Site Geology (Part Section 2.2.2) Available data and reports summarized during 1977-1978 (LETCo Communication Number 173).
Geometry of Salt Dome (Sections 7.1, 10.1, and 13.1) This will provide preliminary data and report for primary salt dome.	Site Geology (Part Section 2.2.2) Available data and reports summarized during 1977-1978 (LETCo Communication Number 173).
Near Dome Mineral Resources (Sections 7.1, 10.1, and 13.1) This will provide data and report for primary salt dome.	
Geology of the Study Area (Sections 6.0, 9.0, and 12.0) This will provide additional details for primary salt dome.	Faulting (Section 2.2.2) Available data and reports summarized during 1977-1978.
No Area Characterization Studies Applicable - Further studies during Site Characterization.	Seismicity (Section 2.2.3) Available data and reports summarized during 1977-1978.
No Area Characterization Studies Applicable - Further studies during Site Characterization.	Stability of Subsurface Materials (Section 2.2.4)
No Area Characterization Studies Applicable - Further studies during Site Characterization.	Slope Stability (Section 2.2.5)
Salt Dome Geology This will provide possible information and relationship between known conditions in existing salt mines and salt cores obtained in seven domes.	Unique Features (Section 2.2.6)
Dome Specific Flooding Studies (Sections 8.2 and 8.3; 11.2 and 11.3; and 14.2, 14.3, and 14.4) This will provide preliminary information and report on Probable Maximum Flooding near seven domes.	Surface Water Hydrology (Section 2.3.1)
Subsurface Hydrology of Study Area. (Section 8.2.2, 11.2.2, and 14.2.2) This will provide preliminary information and report on aquifer characteristics for study areas including estimated travel times and paths of ground water from dome to biosphere.	Ground Water Hydrology (Section 2.3.2)

[1] Refers to chapters in Area Characterization report outline
[2] Refers to sections in Preliminary Safety Analysis Report annotated outline (NUS Corporation, 1978).

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Commercially available data were also identified and purchased. These data were generated in large part by the exploration activities of the petroleum industry and include:

- Geophysical logs
- Sample logs
- Well completion reports
- Regional residual gravity anomaly maps
- Structure contour maps
- Seismic reflection surveys.

Additional data, acquired specifically for this study, either under contract to LETCo or by LETCo personnel, include:

- Deep and shallow boring data
- Ground-level resistivity data
- Field geologic mapping
- Remote sensing (aerial photography and satellite imagery)
- Detailed gravity surveys and gravity modeling
- Reports on generic topics applicable to all study areas and domes.

The locations of wells and seismic data used in Area Characterization studies are shown in Figures 1-5, 1-6 and 1-7. Table 1-2 summarizes the data sources.

Two sources of well data for the Area Characterization studies were: (1) preexisting petroleum, sulfur, and water well records, and (2) geologic and hydrologic records from borings and wells drilled specifically for this study under LETCo direction.

TABLE 1-2.
SUMMARY OF DATA SOURCES

DATA TYPE	SOURCE
Pre-Existing Data	
Oil, gas, water, and sulfur well; geophysical logs and records	Purchased from well log brokers and state regulatory agencies
Common-depth-point seismic data	Purchased from oil companies and independent seismic contractors
Residual gravity anomaly maps	Purchased from a gravity data broker
Regional gravity observations	Purchased from a gravity data broker
Deep structure contour maps	Purchased from a map service company
New Data	
Hydrologic and geologic boreholes	Performed under subcontract to LETCo
Geophysical logs	Commercial logging companies, USGS, and LETCo
Lithologic data	Examination of cores, sidewall cores, and drill cuttings by LETCo consultants and geologists
Paleontological data	Examination of drill cutting and sidewall cores by LETCo paleontological consultants
Near-dome gravity observations	Performed under subcontract to LETCo
Dome gravity modeling	Performed under subcontract to LETCo
Near-dome, high-resolution seismic data	Performed under subcontract to LETCo
Field geologic mapping	Performed under subcontract to LETCo
Ground-level resistivity	Performed by Law Engineering geophysicists
Remote sensing analysis	Performed under subcontract to LETCo
Structure contour and isopach maps and cross sections	Constructed by LETCo geologists

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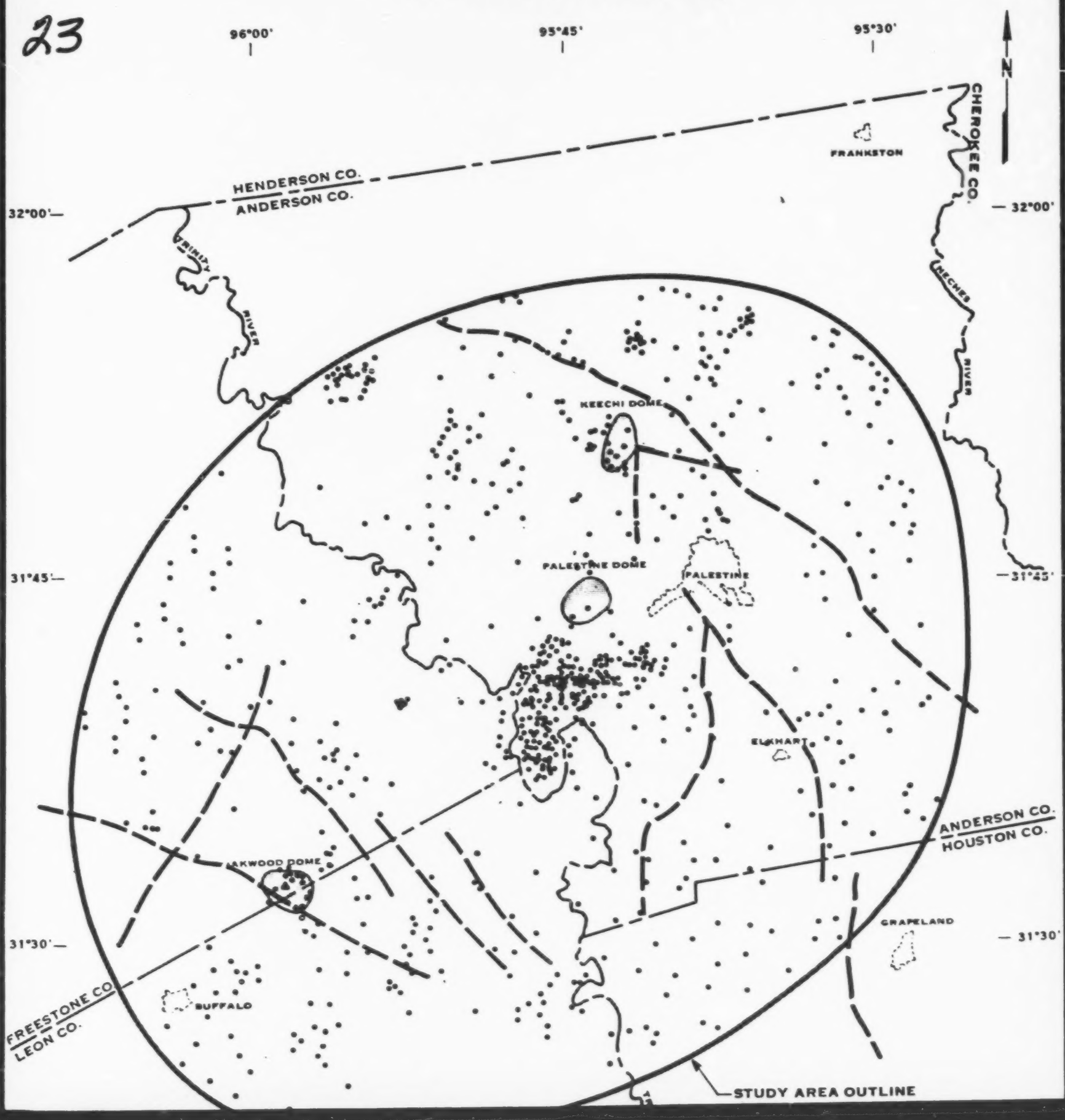

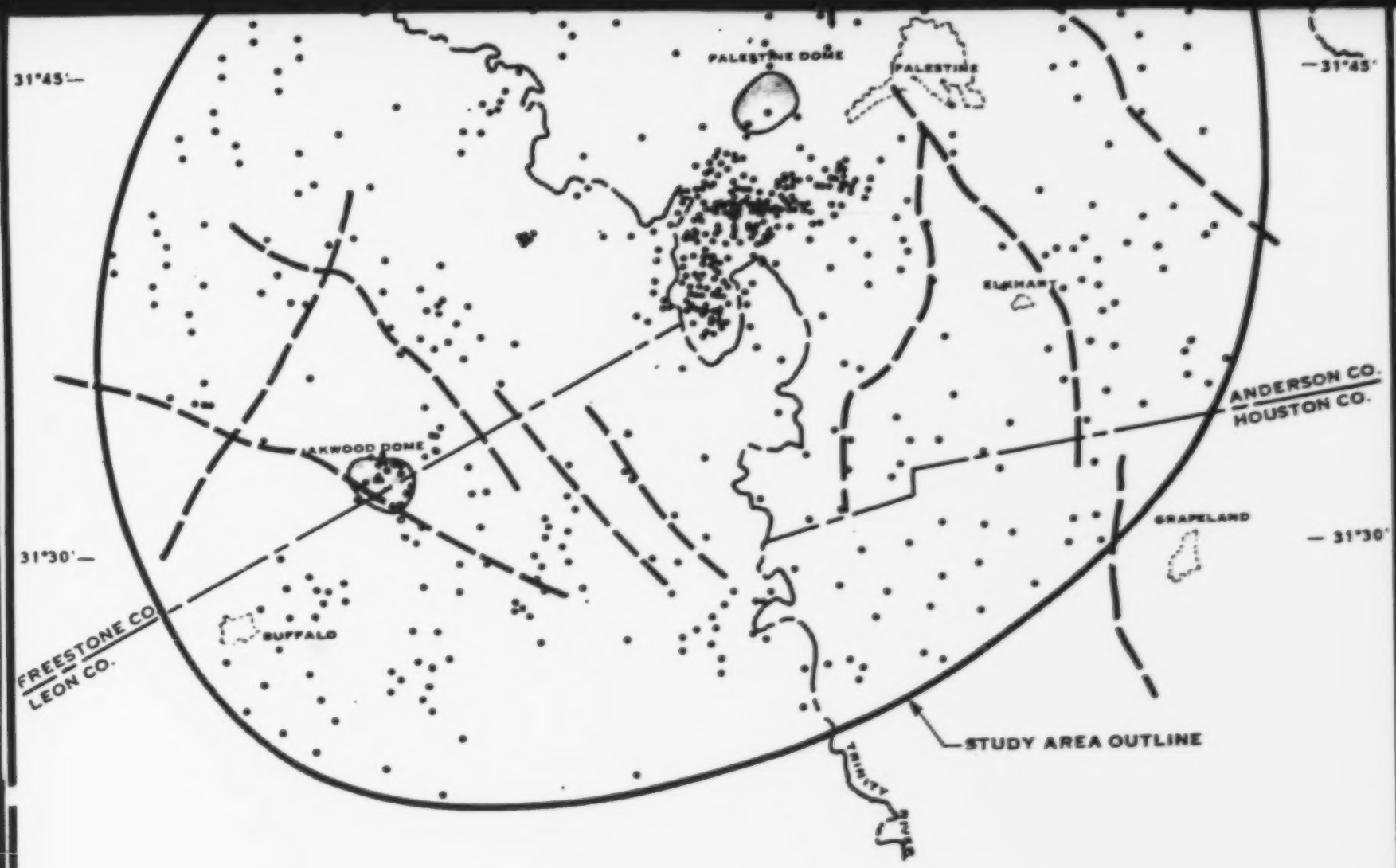

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- COUNTY LINE
- PURCHASED SEISMIC LINES
- AREA OF SALT DOME AT -3000 FEET MSL
- EXISTING WELL
- AREA CHARACTERIZATION BORING
- SALT CORE BORING

5 0 5 MILES

8 4 0 8 KILOMETERS

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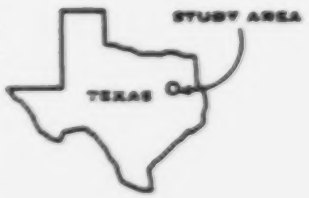

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NATIONAL WASTE TERMINAL STORAGE PROGRAM
GEOLOGIC EVALUATION GULF COAST SALT DOMES

LAW ENGINEERING TESTING COMPANY
MARIETTA, GEORGIA

EAST TEXAS STUDY AREA

LOCATION OF WELLS AND SEISMIC REFLECTION LINES

JOB NO. MV9600 FIGURE 1-5

93°30' 93°15' 93°00' 92°45'

32°30'

32°15'

CLAIBORNE

MINDEN

WEBSTER

GIBSLAND

ARCADIA

LINCOLN

DORCHEAT

BAYOU

VACHERIE DOME

AREA OUTLINE

BIENVILLE

RINGGOLD

BLACK LAKE

SALINE BAYOU

RAYBURN'S DOME

DUGDEMONA

BOEUF

JONESBORO

JACKSON

RED RIVER

NATCHITOCHES

WINN

STUDY AREA

LEGEND

- PARISH LINES
- PURCHASED SEISMIC LINES
- AREA OF CANDIDATE SALT DOME AT -5000 FEET MSL
- EXISTING WELL
- AREA CHARACTERIZATION BORING

5 0 5 MILES

8 4 0 8 KILOMETERS

NORTH LOUISIANA STUDY AREA
LOCATION OF WELLS
AND SEISMIC REFLECTION LINES

JOB NO. MV9600 FIGURE 1-6

NATIONAL WASTE TERMINAL
STORAGE PROGRAM
GEOLOGIC EVALUATION GULF
COAST SALT DOMES

LAW ENGINEERING TESTING COMPANY
MARIETTA, GEORGIA

PREPARED DATE 4/30/80
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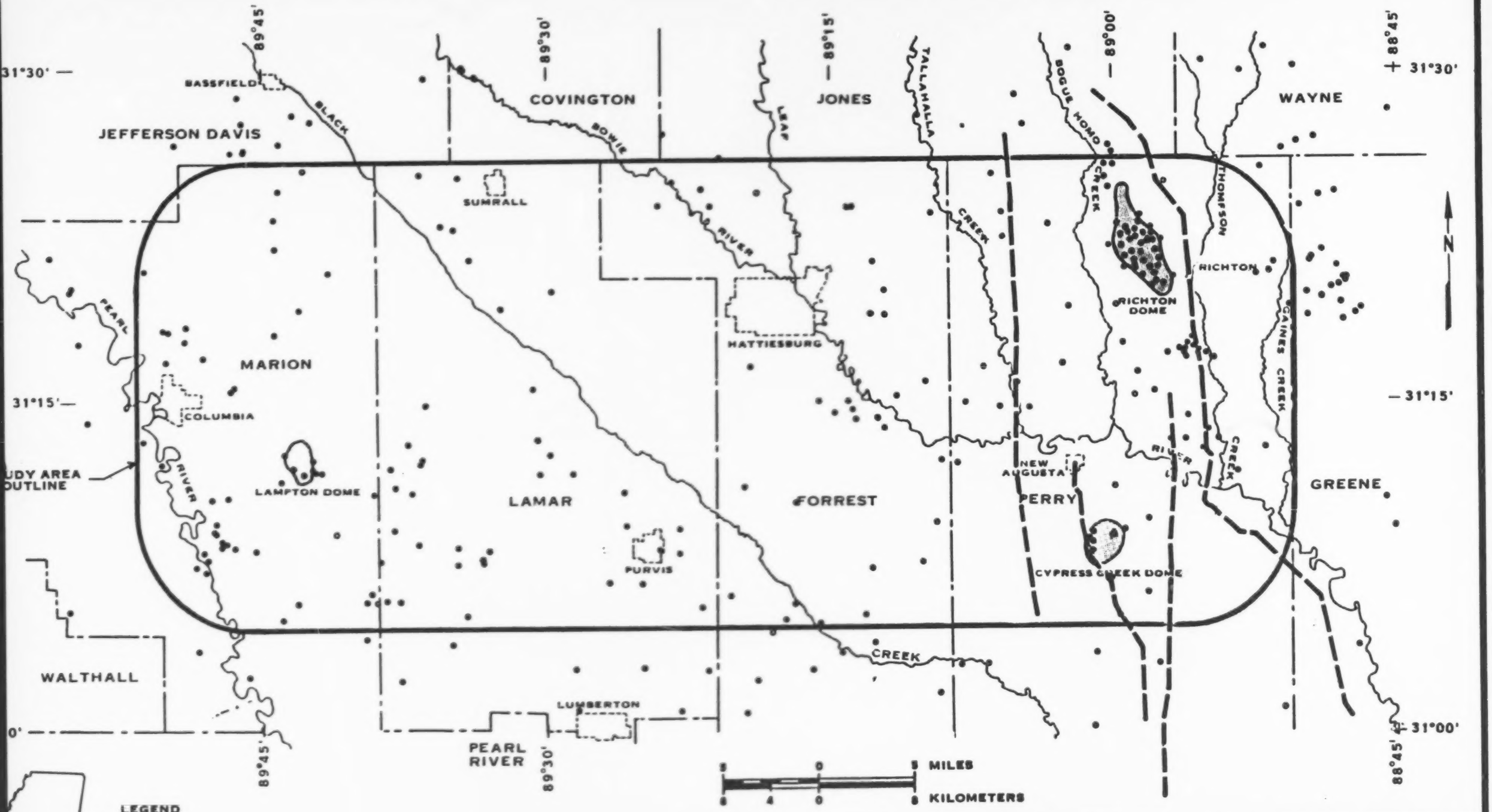

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REVISED	O.K.P.	DATE	11/20/81
REVISED		DATE	
APPROVED		DATE	4/29/80

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NATIONAL WASTE TERMINAL STORAGE PROGRAM
GEOLOGIC EVALUATION GULF COAST SALT DOMES

LAW ENGINEERING TESTING COMPANY
MARIETTA, GEORGIA

MISSISSIPPI STUDY AREA
LOCATION OF WELLS AND SEISMIC REFLECTION LINES

JOB NO. MV9690 FIGURE 1-7

Well data consisted of driller's logs, geological logs, various types of geophysical logs, well completion reports, and well production reports available from state regulatory agencies and commercial sources. The elevations and thicknesses of the various geologic formations were determined by interpretation and correlation of electrical well logs. Well completion reports, scouting reports, and published formation descriptions containing stratigraphic interpretations were used in correlation studies. The correlations were used to construct stratigraphic cross sections, structure contour maps, and isopach maps. Published and commercially available structure maps, as well as purchased residual gravity anomaly maps, were also used to identify and characterize geologic structures. The lithology of the strata was determined by detailed petrologic and paleontologic examination of drill cuttings from borings drilled under the study program, and from interpretation of geophysical well logs. Production data were used to evaluate the mineral resources in the study area, to reconstruct the history of hydrocarbon production, and to predict trends in future exploration.

Approximately 702 km (436 mi) of seismic reflection lines were purchased for the study. The data were processed to varying degrees by the vendors and some of the lines were "migrated" to adjust for reflections from inclined strata. Initial geologic cross sections based on data from wells adjacent to the seismic lines were compared to various prominent reflections and correlated with actual stratigraphic horizons.

Sonic logs from nearby wells were correlated with these beds, then digitized and used to develop synthetic seismograms for determination of the average two-way travel times. Data from synthetic seismograms were combined with velocities deduced from the normal "move-out" obtained from seismic records. This information was used to convert the two-way seismic travel times, furnished in the raw data, to depths of the various reflecting horizons. Once depths to specific beds were calculated, the nature of the geologic structure between well data points was interpreted. The structural data were then incorporated into the structure contour maps and the final cross sections.

Lineaments in the study areas were mapped using LANDSAT (formerly known as Earth Resources Technology Satellite or ERTS), imagery, as well as high-altitude infrared aerial photography. Although lineaments may be produced by various surface influences, some may reflect the presence of fractures in the earth's surface and consequently can be useful for the structural interpretation of an area.

Lineaments were identified as expressions of: (1) linear topographic elements, such as ridges and valleys with definite orientation; (2) apparently controlled drainage, reflected in persistently straight stream segments, chains of lakes or ponds, and abrupt changes in the courses of rivers and streams; and (3) distinct linear boundaries between areas of tonal contrast due to vegetation changes or soil moisture differences.

Regional drainage features appearing on published topographic maps were superimposed on the lineament maps for correlation

analyses. Lineament density and orientation were also analyzed for divergent or anomalous trends. Lineaments were evaluated empirically by observing their coincidence with or deviation from fault planes projected to the surface, within a range of dip angles typical of normal faults on the Gulf Coast. Lineaments not otherwise accounted for were also considered to be leads to possible structural areas requiring further evaluation.

For analyses of the near-dome area, lineaments were superimposed on geologic, topographic, and drainage maps in order to observe correlation with outcrop patterns, topography, and drainage elements. Drainage maps were used to construct contour maps of drainage density and drainage ratios in order to recognize geomorphic evidence of recent uplift or subsidence in the domal areas.

Field geologic mapping was conducted in the study areas and in the vicinities of the candidate domes to define the extent and structural attitude of stream terrace surfaces. The purpose of the mapping was to determine if there is any evidence of warping or other anomalous development of the terraces that might be due to domal movement or compaction of the surrounding sediments. Lithologic mapping of the exposed Miocene, Plio-Pleistocene and Recent beds was used for correlation with the regional geology, for planning shallow subsurface investigations, for geomorphic analyses, and for detecting evidence of surface faulting.

Residual gravity maps of the basin areas were derived from purchased Bouguer data by subtracting the regional gravity effects due to deep-seated structures, isostatic variations, and

density effects associated with lithologic changes. Interpretation of the residual gravity data was performed by computation of the gravity anomaly which would be caused by an assumed model using a modified Talwani-Ewing computer program. This assumed model was then arbitrarily varied until an acceptable fit to the residual gravity map was obtained. Existing well information was used as a control for the model and also, if it was available, to delineate in greater detail the caprock structure and configuration of the top of the salt than could be obtained from the spacing of stations used to derive the gravity maps.

Existing gravity data were used for size and shape modeling of Oakwood, Keechi, and Vacherie Domes. Additional surveys were conducted for Richton, Cypress Creek, Lampton, and Rayburn's Domes to augment the scarce existing data.

Physical representations of the gravity models produced for all seven candidate domes have been constructed in styrofoam. The gravity models were used to define caprock distribution and in the construction of geologic cross sections. Faults interpreted from the regional gravity maps were used for correlation with study area structure contour maps and seismic reflection data to characterize structural anomalies.

The general methodology of floodplain delineation involved the determination of peak discharges at several points on a stream channel associated with the probable maximum precipitation over the basin, and computation of associated water surface profiles. The hydrologic response characteristics that needed to be identified for an analysis of peak discharges included the

absorption capability of the soils in the area and times of concentration of runoff at selected points on streams. The absorption capability of study area watersheds was estimated through the Soil Conservation Services' Soil Curve Number. Time of runoff concentration was calculated using standard methods (Soil Conservation Service, 1975). The stream backwater profile for the probable maximum flood was computed using the Army Corps of Engineers HEC-2 Surface Water Profile Program (U.S. Army Corps of Engineers, 1976). Data were input to HEC-2 for selected stream reaches to compute flood profiles. The program generated flood elevations at selected points using the input data. The area inundated by the probable maximum flood was determined by interpolating between cross sections.

Ground-level shallow electrical resistivity surveying techniques were used in five near-dome areas (Richton, Cypress Creek, Vacherie, Rayburn's, and Oakwood Domes) to aid in the geologic interpretation of the subsurface. The method located vertical and horizontal discontinuities in the electrical resistivity of the near-surface units and, coupled with boring and mapping data, helped in extending formational contacts between known points.

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2 GEOLOGIC SETTING

The purpose for this chapter is to present the reader with background geologic information concerning the Gulf Coast Interior Salt Basin.

The scope of this chapter includes a summary of the regional geology of the Gulf Coast Interior Basin, generic studies related to salt domes and an evaluation of salt basin seismicity. Generic studies, which are specialized topics common to all Area Characterization study areas and domes, were conducted by members of the Technical Advisory Board and by technical consultants. These generic studies are presented in Sections 2.2 through 2.5. The contributing TAB members and technical consultants include:

(1) Salt Dome Growth Rate Studies - Dr. Robert W. Rodgers

(2) Internal Structure of Salt Domes - Dr. Donald H. Kupfer

(3) Winnfield and Grand Saline Salt Domes - Dr. William R. Muehlberger

(4) Interior Salt Basin Seismicity - Dr. H. James Dorman and Dr. Leland T. Long

2.1 GULF COAST REGIONAL GEOLOGY

The regional geology of the Gulf Coastal Province includes discussions of the three Interior Salt Basins (East Texas, North Louisiana, and Mississippi), which are situated near the northern periphery of the Gulf Basin or Gulf Geosyncline (Figure 2-1). In recent years deep drilling, deep penetration seismic reflection surveys, and regional seismic refraction surveys have contributed to a knowledge of the entire Gulf Coastal Province, as a structural basin, and its relationship to the underlying crust.

The Gulf Basin was initiated by block faulting and rifting of the continental crust during Late Triassic time, ultimately resulting in the formation of some of the major boundary fault zones peripheral to the Interior Salt Basins. Its history has been one of repeated subsidence principally as a result of sedimentary loading. Movement of the Louann Salt has affected both sedimentation and structural development in the Interior Salt Basins. The salt migrated into ridges, spawning the diapiric structures with associated faulting and folding. These diapirs are generally believed to have stabilized during the mid-Tertiary.

2.1.1 PHYSIOGRAPHY: The Upper Gulf Coastal Plain is an emergent portion of the Gulf Coastal Province, ranging from 322 to 965 km (200 to 600 mi) wide along the northern perimeter of the Gulf of Mexico (Figure 2-2). The Plain extends inland from the Gulf to the margin of the (preserved) Mesozoic and Cenozoic outcrop belt,

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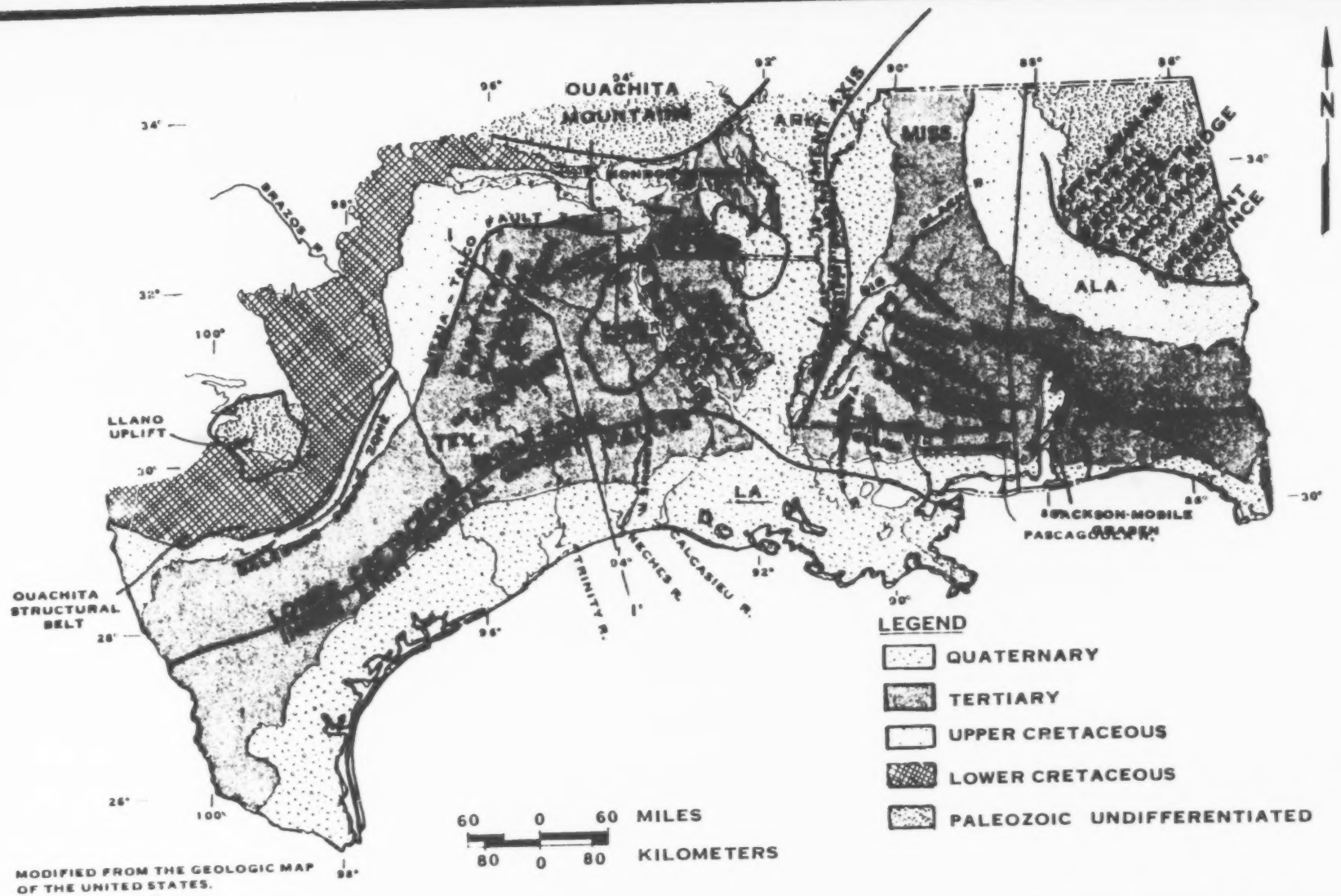

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CROSS SECTION 1-1' IS SHOWN IN FIGURE 2.1 3

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NATIONAL WASTE TERMINAL STORAGE PROGRAM
GEOLOGIC EVALUATION GULF COAST SALT DOMES
LAW ENGINEERING TESTING COMPANY
MARIETTA, GEORGIA

GULF COAST INTERIOR REGION
GENERALIZED GEOLOGIC MAP

JOB NO. MV9600 FIGURE 2-1

FIGURE 2-1

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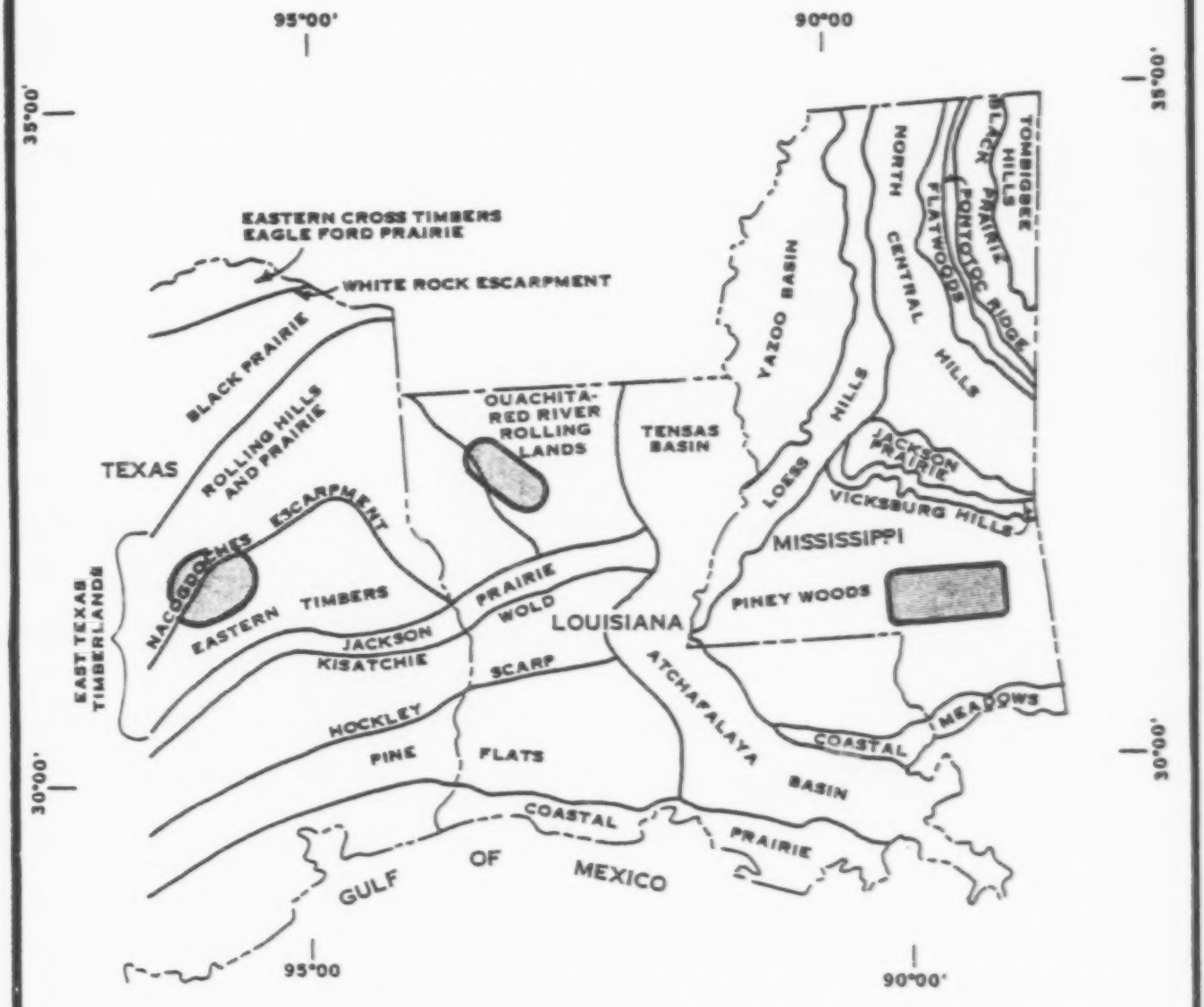

PHYSIOGRAPHY FROM FISK (1944), FENNEMAN (1938), PRIDDY (1960)

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AREA CHARACTERIZATION STUDY AREA

STATE LINE

PREPARED V.R.S. DATE 8/5/80	NATIONAL WASTE TERMINAL STORAGE PROGRAM GEOLOGIC EVALUATION GULF COAST SALT DOMES	GULF COASTAL PLAIN PHYSIOGRAPHIC FEATURES
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APPROVED [illegible] DATE 8/6/80	LAW ENGINEERING TESTING COMPANY MARIETTA GEORGIA	JOB NO. MV9600 FIGURE 2-2
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including the northernmost portion of the Mississippi Embayment at its farthest inland position. From Georgia to northeastern Texas, these Mesozoic and Cenozoic sediments overlap older Paleozoic rocks of the Appalachian Province, the Interior Lowlands, and the Ouachita Province.

Inland elevations average 91 meters (300 ft) above sea level, and the drainage systems generally converge gulfward within the province. The Mississippi River, with its enormous drainage basin, is the largest trunk stream. The river flows southward to the Gulf along the axis of the Mississippi Embayment, upon an alluvial flood plain 40 to 201 km (25 to 125 mi) wide (See Figure 2-1). The lowland effectively divides the higher topography east and west of the valley into the Eastern and Western Hills Physiographic Provinces. Tributary streams of the Mississippi River have also formed valleys. From the standpoint of this study, the most important tributary is the Red River and its nearly 16-km (10-mi) -wide flood plain which traverses the Arkansas-Louisiana-Texas region from the northwest. Tributaries flowing southwesterly in Mississippi include the Homochitto and the Big Black Rivers.

East and west of the Mississippi River drainage basin, trunk streams flow southward directly to the Gulf. East of the Mississippi River are the Amite, Tangipahoa, Pearl and Pascagoula River drainage systems in Louisiana and Mississippi; and to the west are the Calcasieu in Louisiana, and the Sabine, Neches, and Trinity drainage systems in East Texas.

Modern topography is primarily a product of Quaternary drainage incisement associated with broad, continental emergence. The Citronelle-Willis Terraces appear to represent an extensive braided peneplain formed in pre-glacial times. The existing stream patterns were probably established by entrenchment of valleys in the plain caused by the sea level fall associated with the earliest glacial cycle. Successive sea level changes caused deepening and widening of these valleys and the removal of most of the Citronnele-Willis Terrace in the inland portions of the coastal plain. The terrace is preserved discontinuously within a belt parallel to the coast, extending east into Florida and west into Texas along the edges of the Mississippi River Flood Plain. Younger terraces, particularly the Beaumont of Sangamon age, occur coastward from the Citronelle-Willis Belt and extend inland as fluviatile terraces adjacent to the modern stream valleys.

Fluviatile terraces can form as a result of several processes acting either alone or in combination. The processes include adjustment of streams (aggradation or degradation) in response to: (1) changes in base level, (2) changes in precipitation and runoff, (3) changes in sediment load, and (4) local or regional uplift or subsidence.

Traditionally, Pleistocene terraces in the Gulf Coast Region have been attributed to eustatic changes in sea level (base level) caused by continental glaciation in conjunction with regional (epeirogenic) uplift (Fisk, 1938, 1940; Murray, 1948; Martin and others, 1954; Kolb, 1977, 1978, 1979). According to

this theory, streams erode their valleys during glacial periods when sea level is lowered, and aggrade their valleys and develop flood plains during interglacial periods when sea level is raised. A subsequent glacial period will lower sea level, causing streams to erode valleys once again. The previously formed flood plains will then become river-cut terraces.

In order to form a series of terraces at successively lower levels, regional uplift must occur concurrently with repeated sea level fluctuations (glacial and interglacial periods), or each successive glacial period sea level stand must be lower than the previous one.

Adjustment by a stream (degradation or aggradation) to a relative change in base level is neither a consistent nor an instantaneous process along the entire length of the stream and its tributaries. Studies of streams that empty into man-made reservoirs indicate that a rise in base level (construction of a reservoir, for example) may have little effect great distances upstream (Leopold and others, 1964). An abrupt change in the longitudinal profile of a stream (knickpoint) could develop as a result of a base-level lowering. A "wave" of erosion, expressed as a knickpoint, might migrate slowly upstream or else be flattened or otherwise mitigated by changes in the hydraulic variables of the stream itself (depth, width, etc.) or by lithologic differences along the stream bed. It is questionable, therefore, whether every sea level fluctuation (glacial and interglacial period) during the Pleistocene would have affected stream aggradation and degradation in small tributaries within the study area.

Climatic changes, independent of base-level fluctuations, are also known to affect stream aggradation and degradation, leading to the formation of terraces (Leopold and others, 1964). Precipitation and temperature fluctuations will affect the amount and types of vegetation growing in an area and the amount of runoff, both of which affect erosion and sediment transport. The response of a stream to these changes is dependent to a large extent on the existing climate and vegetative cover at the time of the changes. The Northern Gulf Coast probably experienced an increase in precipitation and a decrease in mean annual temperature during glacial periods, resulting in greater runoff and stream flow and greater valley erosion (Frye, 1961). Conversely, the interglacial periods were times of decreased stream flow and increased valley alluviation (Frye, 1961).

Durham and others (1967) suggest that, during glacial periods, meandering streams incised and widened valleys by lateral planation and simultaneously deposited a gravelly substrata on pointbars. The finer-grain top stratum was deposited during late glacial and early interglacial periods.

Neither the processes nor the geologic history that led to the formation of Pleistocene river terraces in the Gulf Coast Region are completely known and understood. A survey of the pertinent literature reveals that even the identification, correlation, and dating of different terrace levels in different parts of the Mississippi, Red, and Ouachita River basins are in dispute (see Kolb, 1979; Durham and others, 1967; and Doering, 1956). For example, comparison of geologic maps for Bossier and

Webster Parishes, Louisiana, (Jones, 1960; Martin and others, 1954) indicates discrepancies in terrace correlation along the common boundary.

It is possible, therefore, that river terraces and other fluvial deposits develop in small tributaries as a result of locally controlled (within the tributary drainage basin) erosion and deposition. Dome-related processes, which may have interacted to produce the terraces, may be deduced from further analysis of the nature and distribution of terraces within salt dome areas.

Modern deltas and flood plains are composed of similar recent deposits. Where the Citronelle-Willis Terrace has been eroded and removed, Tertiary beds are primarily exposed, forming cuestas and vales in response to the differential erosion of the various beds.

2.1.2 MAJOR GEOLOGIC EVENTS: Block faulting and rifting of the continental crust, accompanied by minor basic igneous activity, initiated subsidence in the Gulf Basin in Late Triassic time. The faults, some of which form the northern boundary of the basin, developed along the southern flank of the Late Paleozoic Ouachita Orogenic Belt. Within the basin to the south, subregional crustal blocks developed similarly. This episode is attributed by various authors to early rifting of the continental crust, which elsewhere produced the Atlantic Ocean by sea-floor spreading. An alternative view ascribes the activity to development of an underlying thermal anomaly (Kehle, 1978b).

Throughout the Gulf Coastal Province the establishment of subregional crustal blocks of varying thickness provided a tectonic pattern that influenced subsequent geologic history. Areas of the original, thicker crust were positive, uplifted elements compared to the subsiding elements of new thinner crust. During the Late Triassic to Early Jurassic, this process produced isolated basins in which the Louann Salt was subsequently deposited and buried by younger sediments. These include the three salt basins of interest, as well as several other salt basins of Louisiana, Texas, Mexico and offshore. Intervening positive areas, such as the prominent Sabine Uplift, the Monroe-Sharkey Uplift, and the Wiggins Uplift, contain no salt domes because salt deposition on the uplifted areas was either initially thin, was eroded, or did not occur.

Virtually continuous marine sedimentation throughout the region began in the Late Jurassic. However, this pattern was interrupted in Middle Cretaceous time by general emergence during which the Sabine Uplift, as well as peripheral portions of the Gulf Coastal Province, were exposed to erosion. Marine deposition resumed in the Late Cretaceous, transgressing the continent broadly beyond the original limits of the Gulf Coast Salt Basin, including the subsiding axis of the Mississippi Embayment. Igneous activity recurred in Late Cretaceous, forming the Jackson Dome and producing numerous igneous features in the area of the Monroe-Sharkey Uplift. Both uplifts and an escarpment along the Balcones Fault were subject to Late Cretaceous erosion. Except

for an influx of terrigenous sediments, the Laramide Orogeny in western North America affected only the southwestern margin of the Lower Gulf Coastal Province and did not influence the Upper Gulf Coastal Province. Continental emergence recurred later in the Tertiary (Miocene and Pliocene) and extended progressively southward in association with sedimentation of geosynclinal proportions along the present northern margin of the Gulf of Mexico.

2.1.3 STRATIGRAPHY: Depositional patterns in the northern portion of the Gulf Coastal Province reflect periods of inundation by shallow, quiet seas. These patterns are characterized by limestone and occasional evaporite deposition, alternating with regressive marine conditions, periods of erosion in the hinterland to the north, and associated gulfward extension of deltas. The cyclic deposition has sufficient geographic extent for the resulting stratigraphic units to be mapped on the surface (see Figure 2-1) and in the subsurface throughout the region of the study areas, as represented on the Stratigraphic Correlation Chart in Table 2-1. Major stratigraphic cycles are discussed in the following paragraphs.

Post-salt inundation began in the Late Jurassic with deposition of the Smackover carbonates. Southward regression of the sea, associated with clastic influx from the north during the transition from Jurassic to Cretaceous, was marked by Cotton Valley and Hosston deposits and followed by the Sligo inundation. During Early Cretaceous Comanchean time, an extensive barrier reef developed peripheral to the Gulf Coastal Province gulfward

from the Interior Salt Basins. North of the reef a widespread carbonate lagoon developed in which the deposits extensively overlap the former limits of the Gulf Coastal Province westward across Texas.

Emergence during Middle Cretaceous time was most pronounced in the area of the Sabine Uplift, where the previously deposited Lower Cretaceous sediments were partially eroded. The regressive phase was least noticeable in portions of the Interior Salt Basins, where clastic deposition was almost uninterrupted. Woodbine-Tuscaloosa clastic deposits represent resumed sedimentation in the Late Cretaceous, but the Sabine Uplift was not overlapped completely by deposits of the Austin Group until Middle Gulfian time. By then, extensive deposits of chalk and marl had widely overlapped the northern margin of the Gulf Coastal Province, including the newly formed Mississippi Embayment. Renewal of deltaic deposition, influenced by the uplift of the Laramide Belt to the west, culminated in regional deposition of the Wilcox Group during Early Tertiary time. The succeeding cyclic Claiborne-Jackson-Vicksburg deposition was characterized by interbedded marine and nonmarine formations. A regressive pattern was again initiated by delta building during Late Miocene time, associated with the developing geosyncline along the present coastal region.

2.1.4 GEOLOGIC STRUCTURE: Regional dip of the surficial sediments in the Upper Gulf Coastal Province generally averages about 1 degree in the south; however, major structural elements locally

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TABLE 2-1

GENERALIZED STRATIGRAPHIC CORRELATION CHART
UPPER GULF COASTAL PROVINCE
(COMPILED FROM VARIOUS SOURCES)*

SYSTEM	SERIES	GROUP OR STAGE	EAST TEXAS BASIN FORMATION	NORTH LOUISIANA BASIN FORMATION	MISSISSIPPI BASIN FORMATION	AGE IN MILLIONS OF YEARS
QUATERNARY	RECENT		RECENT	RECENT	RECENT	11,000 yr. bp
	PLEISTOCENE		TERRACE SURFACES AND DEPOSITS EXIST BUT BASINWIDE CORRELATION IS NOT OBVIOUS			SANGAMON (80-100,000 yr. bp)
	PLIO-PLEISTOCENE				CITRONELLE (PRE-GLACIAL)	1.8
TERTIARY	PLIO-MIOCENE		MISSING	MISSING	PASCAGOULA - HATTIESBURG	5.5
	MIOCENE				CATAHOULA PAYNES HAMMOCK	
	?		SH	SH	CHICKASAWHAY	22.5
					BUCATUNNA	
	OLIGOCENE	VICKSBURG	STUDY	STUDY	VICKSBURG undifferentiated	
			AREA	AREA	FOREST HILL/ RED BLUFF	36
	EOCENE	JACKSON			YAZOO	
					MOODYS BRANCH	42
		CLAIBORNE	COOK MTN.	COCKFIELD COOK MTN.	COCKFIELD COOK MTN.	44.5
			SPARTA	SPARTA	KOSCIUSKO (SPARTA)	48
				CANE RIVER	ZILPHA	
			WECHES		WINONA	
			QUEEN CITY REKLAW		TALLAHATTA	
			CARRIZO	CARRIZO	MERIDIAN	58
		WILCOX	WILCOX undifferentiated	WILCOX undifferentiated	WILCOX undifferentiated	53.5
	PALEOCENE	MIDWAY	MIDWAY undifferentiated	MIDWAY undifferentiated	PORTERS CREEK CLAYTON	58 / 65
		NAVARRO (Subsea in Mississippi)	UPPER NAVARRO NACATOCH LOWER NAVARRO	ARKADELPHIA NACATOCH SARATOGA		71
		TAYLOR (Subsea in Miss.)	UPPER TAYLOR PECAN GAP WOLFE CITY LOWER TAYLOR	MARLBROOK ANNONA OZAN	SELMA undifferentiated	76 / 79
	GULFIAN	AUSTIN (Subsea in Miss.)	GOBER MIDDLE AUSTIN	BROWNSTOWN TOKIOE (includes Mexia)		81

*

	PALEOCENE	MIDWAY	MIDWAY undifferentiated	MIDWAY undifferentiated	PORTERS CREEK	63.5
					CLAYTON	65
	GULFIAN	NAVARRO (Subsea in Mississippi)	UPPER NAVARRO NACATOCH LOWER NAVARRO	ARKADELPHIA NACATOCH SARATOGA		71
		TAYLOR (Subsea in Miss.)	UPPER TAYLOR PECAN GAP WOLFE CITY LOWER TAYLOR	MARLBROOK ANNONA OZAN	SELMA undifferentiated	76 79
		AUSTIN (Subsea in Miss.)	GOBER MIDDLE AUSTIN ECTOR	BROWNSTOWN TOKIO (Exclusive Missouri)		81
		EAGLE FORD (Subsea in Mississippi)	SUB-CLARKSVILLE EAGLE FORD undifferentiated	EAGLE FORD	EUTAW	92
		WOODBINE (Tuscaloosa in Miss. and in La.)	WOODBINE undifferentiated	TUSCALOOSA	UPPER TUSC. MIDDLE TUSC. LOWER TUSC.	100
CRETACEOUS	COMANCHEAN	WASHITA	MANESS BUDA GRAYSON MAIN STREET WENO-PAWPAW DENTON FORT WORTH DUCK CREEK SHALE DUCK CREEK LIME-STONE	WASHITA undifferentiated KIAMICHI	DANTZLER	
		FREDERICKS-BURG	KIAMICHI GOODLAND	GOODLAND PALUXY	WASHITA-FREDERICKSBURG undifferentiated	104
		TRINITY	PALUXY UPPER GLEN ROSE FERRY LAKE LOWER GLEN ROSE	RUBY FERRY LAKE RODESSA JAMES PINE ISLAND	PALUXY MOORINGS PORT FERRY LAKE RODESSA PINE ISLAND	105 106 107 109 113
	COAHUILAN (Off shore)	NUEVO LEON AND DURANGO (Off shore)	PETTET TRAVIS PEAK	SLIGO HOSSTON	SLIGO HOSSTON	125
	UPPER	COTTON VALLEY	KNOWLES SCHULER BOSSIER	DORCHEAT SHONGALDO BOSSIER	COTTON VALLEY undifferentiated	143
JURASSIC		LOUARK	GILMER BUCKNER SMACKOVER	HAYNESVILLE SMACKOVER	HAYNESVILLE-BUCKNER SMACKOVER	
	LOWER	LOUANN (Extent age uncertain) (Louisiana Grp. in La.)	NORPHLET LOUANN SALT WERNER	NORPHLET LOUANN SALT WERNER	NORPHLET LOUANN SALT WERNER	
TRIASSIC	UPPER		EAGLE MILLS	EAGLE MILLS	EAGLE MILLS	

PRE-MESOZOIC

* FORMATIONAL NAMES ARE THOSE MOST WIDELY USED BY VARIOUS LOCAL GROUPS AND REPRESENT STATE GEOLOGICAL SURVEY USAGE.

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TABLE 2-1

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NATIONAL WASTE TERMINAL STORAGE PROGRAM
GEOLOGIC EVALUATION GULF COAST SALT DOMES

LAW ENGINEERING TESTING COMPANY
MARIETTA, GEORGIA

UPPER GULF COASTAL PROVINCE
GENERALIZED STRATIGRAPHIC CORRELATION CHART

JOB NO. MV9600 TABLE 2-1

interrupt this trend (Figure 2-3). Southwesterly dips on the eastern side of the Mississippi Embayment and southeasterly dips on the western side produce surface outcrop belts which extend far inland, outlining the northern configuration of the embayment.

Basement block faults, mainly of Late Triassic age, as well as younger flexure fault zones, developed peripheral to the initial Gulf Coastal Province. Faults in these zones show evidence of recurrent movement as indicated by the graben blocks of the Pickens-Gilbertown Fault Zone to the east in Alabama and Mississippi, extending westward to the South Arkansas Fault Zone and the Mexia-Talco and Balcones Fault Zones in central Texas. The Mount Enterprise Fault Zone is a flexure fault to the southeast of the East Texas Basin. Growth faults, featuring deposition contemporaneous with displacement, are common in the geosynclinal deposits to the south. These faults are not tectonic; they are developed by the continual creep of newly deposited sediments across structural declivities, but they reflect the continued subsidence of the Gulf Basin in Recent geologic time.

The most effective structural agent to influence local basin development was the movement of the Louann Salt in response to the uneven distribution of the overlying sediments. As early as Late Jurassic, during deposition of Smackover sediments, mobilization of the salt commenced with migration into linear ridges and continued as additional sedimentation occurred. Where the salt was sufficiently thick and adjacent sedimentation continued,

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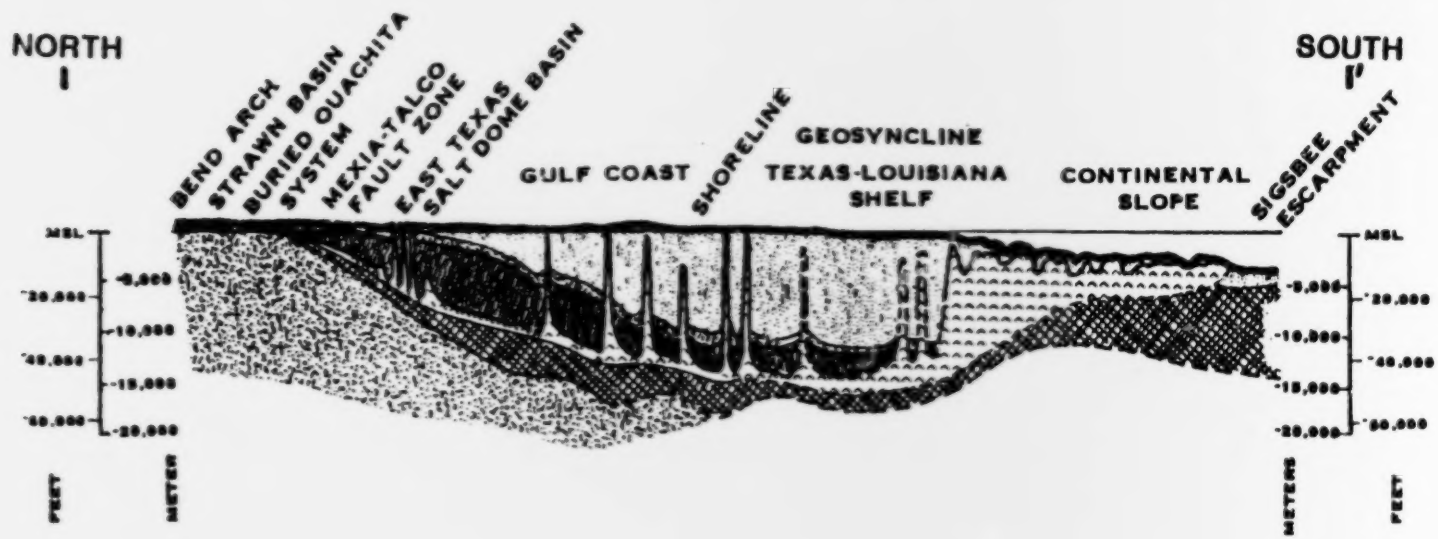

50 0 50 MILES

100 0 100 KILOMETERS

LEGEND

- TERTIARY
- UPPER CRETACEOUS
- LOWER CRETACEOUS
- JURASSIC-SALT
- PERMO-TRIASSIC
- PALEOZOIC UNDIFFERENTIATED

CROSS-SECTION MODIFIED FROM MARTIN AND CASE, 1974

CROSS-SECTION LOCATION SHOWN IN FIGURE 2-1

FIGURE 2-3

PREPARED	RRR	DATE	11/25/81
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NATIONAL WASTE TERMINAL STORAGE PROGRAM

GEOLOGIC EVALUATION GULF COAST SALT DOMES

LAW ENGINEERING TESTING COMPANY
MARIETTA, GEORGIA

GULF COAST REGION
GENERALIZED NORTH - SOUTH
CROSS SECTION

JOB NO. MV9600 FIGURE 2-3

pillowing and then diapirism occurred in the form of salt domes. Salt migration ceased after diapirism climaxed and movement finally stabilized during the Middle Tertiary in the Interior Salt Basins and during the Late Tertiary or Pleistocene in the Coastal Salt Basins. Offshore doming apparently still continues, associated with modern sedimentation offshore. The timing of salt migration and stabilization in the Interior Salt Basins is reflected in the gradual gulfward shift of the centers of clastic deposition from Cretaceous through Recent times.

2.2 SALT DOME GROWTH RATE STUDIES

This report section, compiled with the assistance of Dr. Robert W. Rodgers, consultant, describes the various theories of salt dome growth, compares measurement techniques for determining growth rates, and presents some of the existing growth rate calculations. The seven candidate domes of Area Characterization have been tentatively evaluated to determine the growth state attained.

2.2.1 INTRODUCTION: The concept that salt domes have been formed by upward plastic flow of salt derived from a sedimentary salt bed has been accepted for more than 60 years. The origin and growth of salt structures have received comprehensive review by Halbouty (1979a and b).

Although tectonic stresses can result in salt mobilization, they are not requisite to its occurrence. Sedimentary loading is generally thought to provide sufficient motivation for the mobilization of the salt (Harbort, 1913). Salt movement has been ascribed to its lesser specific gravity compared to the surrounding sediments, resulting in buoyant upward movement of the salt (Arrhenius, 1912).

According to Barton (1933), the accumulating sediments subside as the sedimentary basin is filled, whereas the salt structure remains more or less constant in depth. Thus, the surrounding sediments subside downward past the salt column. Horizontal flowage of salt from the mother bed moves in toward

the base of the salt column and builds the base downward in reference to the surface, a process Barton called "downbuilding".

For buoyancy alone to mobilize the salt, a sedimentary cover of several thousand feet is required because unconsolidated sediments at shallower depths have a lower density than the salt (Kehle, 1980). Stratigraphic evidence demonstrates salt mobilization during deposition of the sediments immediately overlying the salt, such as the Smackover Formation (Hughes, 1960). This supports the concept that irregularities in the overlying sediments or in the salt or in the substrata beneath the salt are reponsible for initial movement (Halbouty and Hardin, 1956). The effectiveness of such variables in producing salt mobilization has been demonstrated in model studies (Parker and McDowell, 1951, 1955). Kehle (1980) emphasizes the importance of uneven sediment loading, whereas Paulson (1969) notes that the early formation of salt ridges in Mississippi may be due to escarpments over which the salt was deposited in a monoclinal configuration. He ascribes the escarpments to preexisting wrench faults that may have remained active during salt deposition or later.

Implicit in these models is the purpose of recognizing stages in the development of the salt structure. The different models define whether or not the salt movement occurred as a single surge or pulse, in a series of pulses, or as continuous in time at a uniform or nonuniform rate. The models also attempt to determine if dome development is, in fact, complete, with no further movement possible.

2.2.2 MODELS OF DOME DEVELOPMENT: Two major types of salt structures have long been recognized: the deep-seated nonpiercement structure, often in pillows or ridges, and the shallow piercement dome (Nettleton, 1934). The nonpiercement structure is the earlier stage of development from which the piercement domes or diapirs evolve (Trusheim, 1960). On the basis of studies of German domes, Trusheim recognized four stages of growth:

(1) Initial stage of salt movement

(2) Pillow stage

(3) Diapir stage

(4) Post-diapir stage.

A similar development sequence was described by Kupfer (1975) for Gulf Coast salt domes. Figure 2-4 presents a developmental sequence modified from Halbouty (1967).

Citing studies by Loocke (1978) of Hainesville Dome in East Texas as an example, Kehle (1980) has noted that massive extrusion of salt, causing collapse of the underlying pillow, may also occur. The interpretations of Trusheim, Kupfer, and Kehle similarly recognize initial salt movement as horizontal, with the formation of pillows or ridges followed by a vertical diapiric movement and ultimate stabilization, usually during burial by the last stages of sedimentation in the area.

2.2.3 CRITERIA FOR MEASUREMENT OF DOMAL MOVEMENT: Several criteria have been used to measure domal development, to correlate the movement with geologic time, and to establish rates for the

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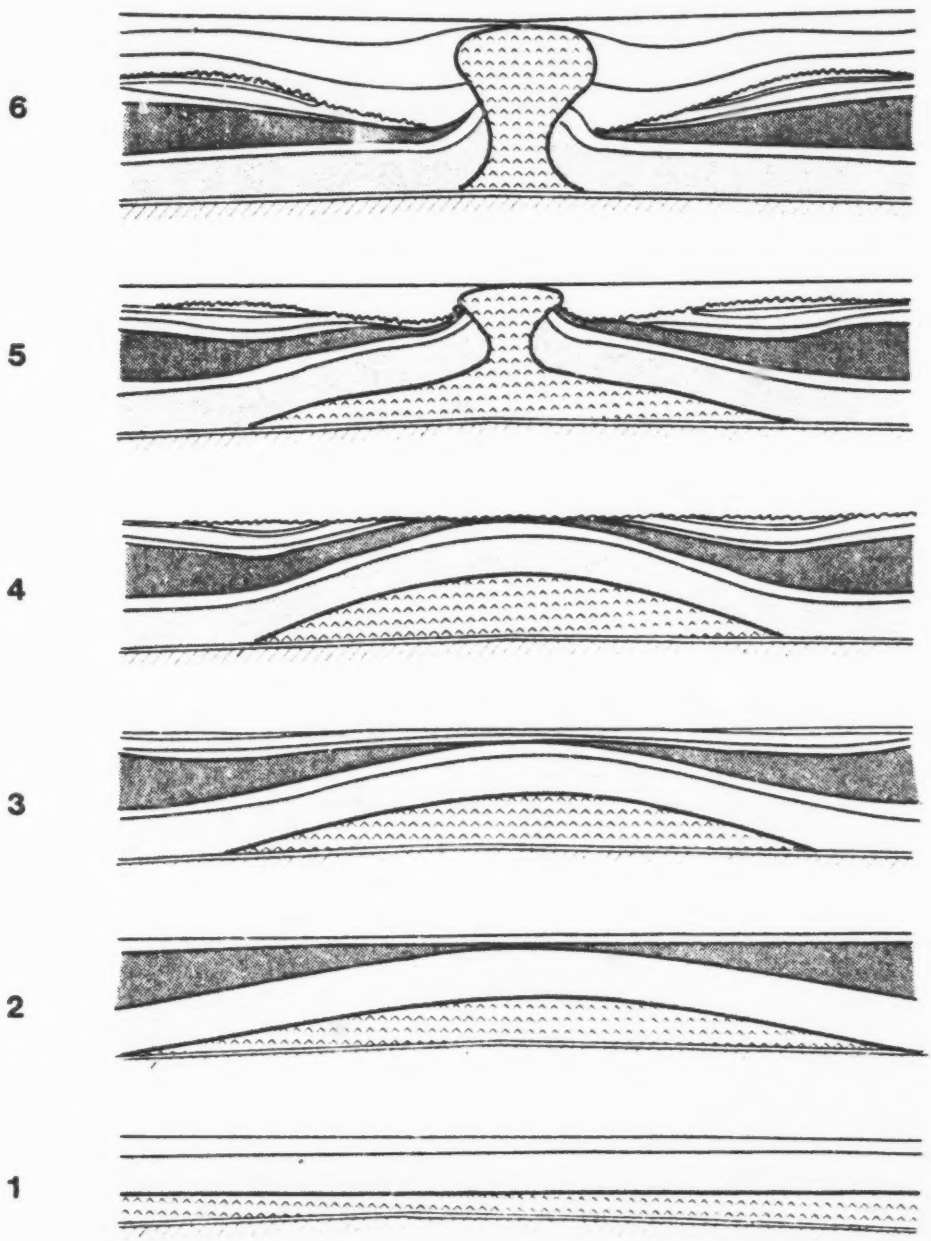

DIAGRAMATIC DEVELOPMENT OF A SALT STOCK FROM (2) AN EARLY RIDGE OR PILLOW STAGE TO (5) SHALLOW PIERCEMENT OR A DIAPIRIC STAGE TO (6) ULTIMATE STABILIZATION.

(MODIFIED FROM HALBOUTY, 1967)

PREPARED LLL DATE 11/25/81 REVISED ——— DATE ——— REVISED ——— DATE ——— APPROVED DEP DATE 11/25/81 T-1489-1	NATIONAL WASTE TERMINAL STORAGE PROGRAM GEOLOGIC EVALUATION GULF COAST SALT DOMES LAW ENGINEERING TESTING COMPANY MARIETTA, GEORGIA	DOMAL GROWTH STAGES FOR A SHALLOW PIERCEMENT DOME JOB NO. MV9600 FIGURE 2-4

BEST DOCUMENT AVAILABLE

development of the domes. Among the criteria which have been used by various investigators to determine domal development are:

(1) Volume of salt calculations and development of rim synclines

(2) Stratigraphic thinning on top of the dome

(3) Structural relief of sediments over the dome

(4) Measurements of fault displacement (growth fault)

(5) Changes in the angle of dip of sediments with time

(6) Development of caprock on the domes

(7) Unconformities associated with the domes.

An understanding of the regional and local depositional history within the salt basins is essential to the construction of a model for dome development and the determination of times and rates of development. This would include the pre-salt surface (pre-Mesozoic) and its influence on thickness of the salt, which may determine the ultimate position of a dome within the basin.

To measure dome development rates the detailed stratigraphy adjacent to and over the dome, the age of the salt intrusion, and the mode of salt intrusion must be known or interpreted. Structural and isopach maps of successive overlying formations help define the stages of domal development so that a model for salt dome growth can be constructed. Determination of several such models develops answers to pertinent questions. Is each salt dome unique with respect to its development? To what extent can we compare domes? Is a model, based on the analysis of a specific dome, applicable to all domes within a basin?

2.2.3.1 Volume Calculation and the Development of Rim Synclines: Rim synclines are structural lows peripheral to salt domes and are presumed to have resulted from subsidence of the overlying beds due to salt withdrawal from the basin into the dome. Volume calculations give the best control on the rate of salt movement with time because they involve both vertical and horizontal movement. The data required are obtained from isopach maps of stratigraphic units on which the geometry of the rim syncline and salt withdrawal basin can be quantitatively determined. The procedure involves measurements of radii of rim synclines, the salt stock, and the thickness of the original salt bed, as explained by Kumar (in Martinez and others, 1977). Rim synclines follow a pattern of migration inward toward the dome on successively younger horizons and upward through time.

2.2.3.2 Stratigraphic Thinning on Top of the Dome: Stratigraphic thinning is commonly associated with the arching of strata near and over a salt structure. In some cases, thinning may reduce by more than half the normal regional thickness of an individual sequence. If the horizontal surface of deposition is maintained while the salt is rising from the original horizontal source bed, the thickness of sediments accumulated is minimal at the crest of the dome. Kumar (in Martinez and others, 1977) stated that stratigraphic thinning over the dome is basically a measure of the corresponding amount of salt uplift during the deposition of the particular stratigraphic unit. Such thinning

must be compared to the normal regional thickness rather than to the abnormal local thicknesses in the bordering rim synclines.

2.2.3.3 Structural Relief of Sediments over the Dome: As a salt dome develops it may arch or uplift the previously deposited overlying strata. The structural relief on top of the beds is proportionate to the vertical rise of the salt. The total amount of structural relief divided by the total length of time since the deposition of any unit gives the average rate of uplift of that stratigraphic unit from the time of deposition to the present.

2.2.3.4 Measurement of Fault Displacement (Growth Faults): The amount of thickening of a stratigraphic unit across a growth fault can be divided by the depositional time interval for that unit to determine the rate of uplift along the fault. Also, if the amount of displacement along a fault is determined to be caused by vertical movement of the salt, the rate of uplift may be construed to be the rate for vertical dome growth.

2.2.3.5 Changes in the Angle of Dip of Sediments with Time: By plotting the average angle of dip of beds on the periphery of a salt dome against the age of the strata in millions of years, a rate of movement for the dome may be determined. Each deformation is added to each earlier deformation, and a "rate of change" of dip (slope of the line) may be determined as stated by Kupfer (in Kupfer and others, 1976).

2.2.3.6 Development of Caprock over the Dome: Questions regarding the origin of caprock have not been resolved. However, if the caprock forms as a result of dissolution, then the thickness of caprock may be related to the rate of dome growth (Martinez, 1974). Muehlberger (1976) noted that a relationship may exist between the thickness of caprock and the amount of salt dissolved from a salt stock. Thickness of caprock is also dependent on the percentage of anhydrite in the domal salt. For example, if the salt stock contains 3 percent anhydrite by volume, then approximately 1,006 meters (3,300 ft) of salt would have to be removed by solution in order to produce a caprock 30 meters (100 ft) thick.

2.2.3.7 Unconformities Associated with the Dome: Unconformities may be especially useful in determining the state of development of a particular salt dome. If the relative ages of the strata immediately above and below an unconformity are known, and if the amount of missing section associated with that unconformity is known, an estimate for the growth rate associated with the unconformity may be determined.

2.2.3.8 Assumptions and Constraints on Dome Development Criteria:

(1) The surface of deposition of each stratigraphic unit has been horizontal throughout the period of its deposition.

(2) The effects of compaction of sediments, as well as tensional stretching of the upturned beds associated with a

salt dome, are not significant; however, Kupfer (1975) has emphasized the effects of compaction.

(3) The thinning of a stratigraphic unit caused by a unconformity, as well as the thickening of beds resulting from growth faulting, are negligible (where undeterminable for lack of data).

(4) The structural relief on the shallowest stratigraphic marker bed is a result of salt uplift.

(5) The effects of dissolution collapse of the strata close to the top of the salt domes are negligible.

(6) Reasonably accurate age dates are available and reliable.

(7) Stratigraphic units used as marker horizons associated with the dome can be considered as time units.

2.2.4 RATES OF DOMAL GROWTH: Utilizing the methods discussed above, growth rates were calculated by Netherland, Sewell and Associates (1976) for east Texas domes and by Kumar (in Martinez and others, 1977) for north Louisiana domes. Kumar summarized the minimum and maximum range of growth rates from these data as follows:

TABLE 2-2.
RANGE OF GROWTH RATES FOR LOUISIANA AND TEXAS DOMES

Stratigraphic Interval	North Louisiana Domes (mm/yr)*	East Texas Domes (mm/yr)
Cenozoic	0.001-0.027	No Data
Tertiary	No Data	0.003-0.043
Upper Cretaceous	0.001-0.019	0.014-0.029
Lower Cretaceous	0.009-0.042	0.026-0.054
Upper Jurassic	No Data	0.153 (average)

*To convert to inches, multiply by 0.03937 T-2101-0

The highest growth rate cited is the east Texas value for the Upper Jurassic at 0.153 mm/yr (0.006 in/yr) or about 152 m/MY* (about 500 ft/MY). Values for Cretaceous and Tertiary growth rates range from 0.001 mm/yr (0.00004 in/yr) or about 0.9 m/MY (about 3 ft/MY) to 0.054 mm/yr (0.002 in/yr) or about 238 m/MY (about 780 ft/MY).

The overall average Cenozoic growth rate of the 12 domes in North Louisiana for which Kumar obtained values ranges from 0.002 mm/yr (0.00008 in/yr) or about 1.8 m/MY (about 6 ft/MY) to 0.009 mm/yr (0.0003 in/yr) or about 9.1 m/MY (about 30 ft/MY). Netherland, Sewell and Associates (1976) reported 0.006 mm/yr (0.0002 in/yr) or about 5.8 m/MY (about 19 ft/MY) for post-Wilcox time for Texas domes. These computations are averages that include Eocene time when Claibornian sediments were still being deposited in both areas. It is likely that movement was faster during the early period when sedimentation was occurring and ultimately ceased when deposition in the area ceased.

2.2.5 EXTRUSION DOMES: Several interior salt domes occur within enormous structural basins which are actually large, encircling rim synclines.

2.2.5.1 Hainesville Dome: Loocke (1978) investigated the Hainesville Dome and the associated Mineola Basin in east Texas (Figure 2-5). He concluded that the basin was the result of extrusion

*MY is the abbreviation for million years in this report.

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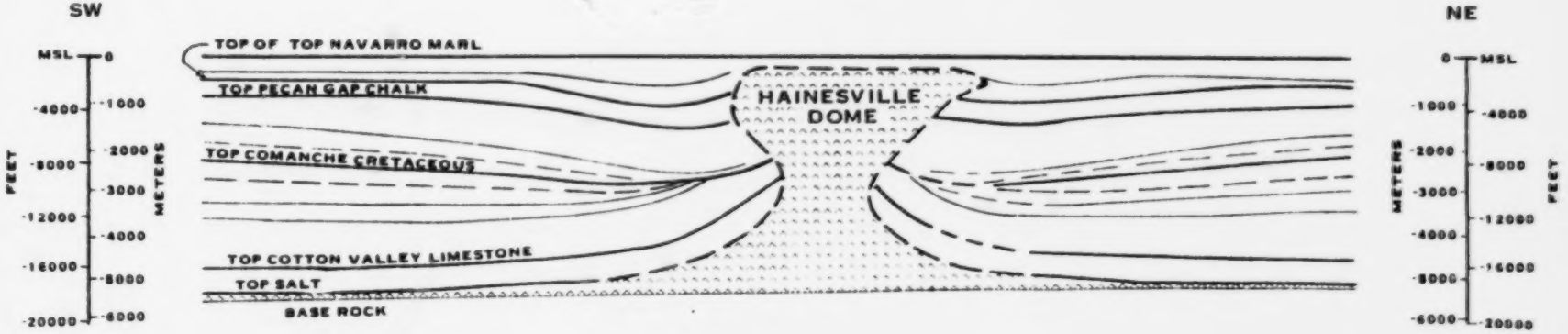

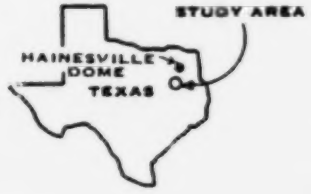

LEGEND

- SALT DOME
- DOME CONTACT
- FORMATION/GROUP CONTACT DASHED WHERE INFERRED

2 0 2 MILES

2 0 2 KILOMETERS

CROSS-SECTION FROM LOOCKE, 1978

PREPARED [illegible] DATE 11/25/91	NATIONAL WASTE TERMINAL STORAGE PROGRAM GEOLOGIC EVALUATION GULF COAST SALT DOMES	SCHEMATIC CROSS SECTION THROUGH HAINESVILLE DOME
REVISED ____ DATE ____	LAW ENGINEERING TESTING COMPANY MARIETTA, GEORGIA	
REVISED ____ DATE ____		
APPROVED DGP DATE 11/25/91		JOB NO. MV9600 FIGURE 2-5
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FIGURE 2-5

of large volumes of salt which had formerly accumulated in a large salt pillow. Evidence for extrusion is twofold:

(1) Reconstruction of the cross-sectional configuration of formations through time, based on interpretation of seismic data, indicates eventual surface truncation of the salt pillow in Early Cretaceous time, thus providing an avenue for salt extrusion.

(2) The size of the subsequent rim syncline suggests the movement of 230 km^3 (56 mi^3)* of salt. Seventy-eight cubic kilometers (19 mi^3) of salt remain in the salt dome and its pronounced overhang, and 64 km^3 (15.5 mi^3) or less may have been dissolved in the shallow subsurface to form the present caprock. Thus, 88 km^3 (21.5 mi^3) or more of salt is hypothesized to have been extruded.

In a report for Law Engineering Testing Co., Kehle (1978b) postulated that domes, passing through the truncation and extrusion stage, stabilize when all the salt is evacuated from the underlying salt pillow. Subsequently, sediments commonly bury these domes.

In an expansion of his 1978 report, Kehle (1980) computed a maximum vertical salt velocity through the dome during the extrusion period of 610 m/MY (2,000 ft/MY) at Hainesville Dome. This compares to a slower vertical growth rate of the pillow of nearly 244 m/MY (800 ft/MY) just prior to exposure of the salt core at the surface.

2.2.5.2 Minden Dome: The Minden Basin, associated with Minden Dome in north Louisiana, is similar in size to the Mineola Basin. The dome (Figure 2-6) was studied by Law Engineering (1978d)

*Kehle (1978b, 1980) quotes this figure at 184 km^3 (45 mi^3).

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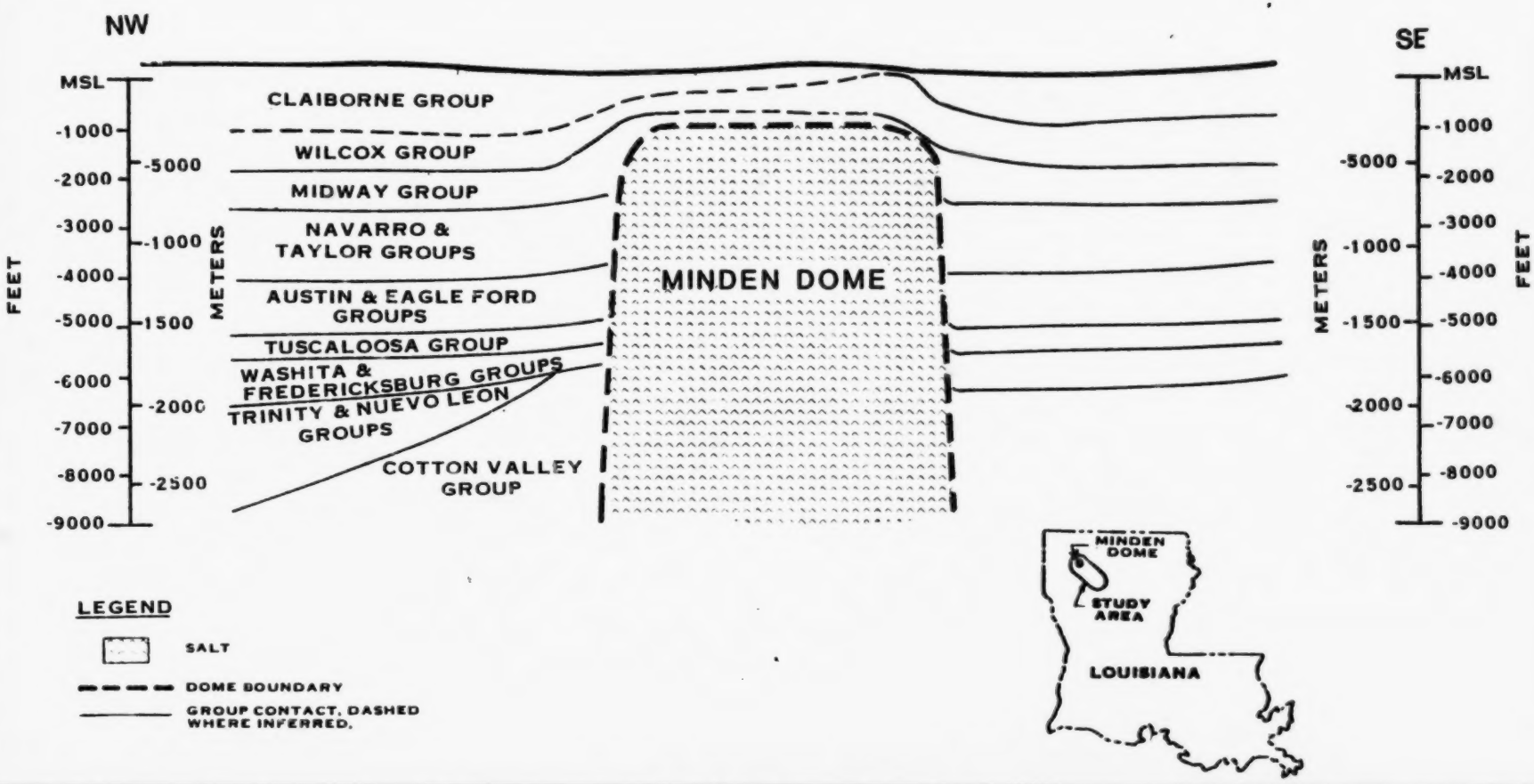

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NATIONAL WASTE TERMINAL STORAGE PROGRAM
GEOLOGIC EVALUATION GULF COAST SALT DOMES
LAW ENGINEERING TESTING COMPANY
MARIETTA, GEORGIA

SCHEMATIC CROSS SECTION THROUGH MINDEN DOME

JOB NO. MV9600

FIGURE 2-6

FIGURE 2-6

in order to test the model of the Hainesville Dome. Although the Hainesville conclusions are based primarily on seismic data that permit interpretation as deep as the mother salt bed, the Minden conclusions are based on numerous well logs which do not penetrate the deeper horizons.

Evidence for truncation of the salt at Minden Dome is indirectly provided by the development of uplifted and differentially eroded fault blocks, mainly on the south side of dome, at the end of Coahuilan time (Pine Island Formation), and mainly on the northwest side of the dome during Comanchean time (Kiamichi Formation).

The Minden study derived growth rates of the growing dome from structural uplift data. These structural methods yielded a maximum rate of 0.20 mm/yr (0.008 in/yr) or 197 m/MY (645 ft/MY) during the Comanchean Stage (Rodessa to Kiamichi Formations) based on evidence from the uplifted fault block.

Isopach data indicate a much higher rate of salt evacuation, presumably a result of extrusion, but subsurface data are so sparse that the values were not calculated. The highest rates calculated from the isopach data are 0.22 mm/yr (0.009 in/yr) or 235 m/MY (772 ft/MY).

Stratigraphic methods yield greater uplift values during extrusion and salt dissolution to form caprock because they reflect the rate of the vertical movement of the salt within or through the diapir, whereas structural methods indicate the upward movement of the salt structure.

2.2.5.3 Cypress Creek Dome: Cypress Creek Dome, which is a candidate dome, and the associated Perry Basin in south Mississippi, provide another example of probable salt extrusion.

Structural maps of the Perry Basin on the Middle Cretaceous Lower Tuscaloosa Formation (Figure 12-13, Volume 6) and on the Paleocene Porters Creek Formation (Figure 12-15, Volume 6) are similar. Approximately 914 meters (3,000 ft) of structural relief exists in the basin, thus indicating that basin development occurred subsequent to Porters Creek deposition. The volume of the basin, based on the Porters Creek structural map, is approximately 281 km^3 (68.6 mi^3).

The isopach map of the overlying Wilcox Group (Figure 12-21) indicates that approximately 223 km^3 (54.5 mi^3) of sediments were deposited in the basin during Wilcox time, approximately 80 percent of the total. Thick caprock exists along the dome flanks at Wilcox level with a computed volume of 1.39 km^3 (0.34 mi^3). Based on 3 percent* anhydrite in the salt, this represents 46 km^3 (11.33 mi^3) of salt dissolved in the newly deposited Wilcox sediments at the time. The high salinity of water in the Wilcox of the Perry Basin may be derived from salt dissolved at that time. The remainder of the salt, 168 km^3 (41 mi^3) in volume, represents loss by extrusion. The cross section of the dome at Wilcox level is 10.1 km^2 (3.9 mi^2). Thus, an 18-km (11-mi) column of salt extruded from the salt diapir to account for the increase in the Perry Basin sediments

*Loocke (1978) used a lower value of 1 percent anhydrite for Hainesville Dome. The higher value here is used because of the amount of anhydrite in the Cypress Creek salt core.

resulting from evacuation of the underlying salt. This is a vertical rate of 2.0 mm/yr (0.08 in/yr) or 2,218 m/MY (7,277 ft/MY), assuming an 8-million year duration for the Wilcox. Compared to this large salt volume, 8.85 km^3 (2.16 mi^3) of salt remain today in the dome above the Wilcox level.

The structural map on the top of the Vicksburg (Figure 12-20) displays 48.3 km^3 (11.8 mi^3) of volume for the Perry Basin, suggesting that degree of basin subsidence in Miocene and later time. This may be caused completely by salt evacuation from beneath the basin, or the compaction of basinal sediments may have been partly or completely responsible. Since the salt dome is 8.5 km^2 (3.3 mi^2) in lateral extent at that level, this indicates 5.6 km (3.5 mi) of vertical salt movement since Vicksburg time, an average of 0.025 mm/yr (0.0010 in/yr) or 241 m/MY (792 ft/MY), if salt evacuation alone were responsible. However, because the Wilcox sediments alone are more than twice as thick in the basin as their regional thickness outside the basin, compaction of 40 percent could account for the entire maximum subsidence of 457 meters (1,500 ft) of the basin in post-Wilcox time.

The role of compaction has been emphasized by Kupfer (1975). Whereas the solid, nonporous salt in the domes does not compact, considerable compaction occurs in the adjacent sediments. This produces arching and possible faulting of the sediments overlying the domes. Similarly, rim synclines, which contain greater sedimentary thicknesses than the surrounding areas, may continue to receive thicker sediments due to compaction rather than to salt

apparent domal growth by salt movement laterally into the dome long after the salt has really stabilized.

2.2.6 COMPARISON OF EXTRUSION AND OTHER DIAPIRIC DOMES: The three domes discussed above are atypical in the large size of their rim synclines which developed during their extrusion stages. These domes additionally evidenced abnormally large salt pillows from which the extruded salt was withdrawn in the pre-diapiric stage. They also demonstrate considerably faster rates of vertical salt movement than the rates described earlier for other domes.

Kehle (1978a, 1980) emphasizes that an extrusion dome in which the pillow salt has been depleted is consequently stabilized because no more salt is available for upward movement in the diapir; thus, the domes are ultimately buried by overlying sediment. While this may be the case for Hainesville Dome, it appears that extrusion domes do not necessarily have to have all the pillow salt evacuated in order to stabilize and reach burial stage. For example, seismic lines in the vicinity of Cypress Creek Dome indicate the presence of the Louann Salt at depth (Figures 12-10, 12-26, 12-30, Volume 6).

Many domes have rim synclines sizable enough to indicate considerable upward movement of salt during the diapiric stage, but not necessarily enough to require an extrusion as an explanation. Also, as Kehle notes, beds on some domes dip away from the dome rather than displaying an encircling rim syncline. These domes

have nonetheless developed by diapirism, if not extrusion, and many are buried, indicating current stability. In the context of cessation of sedimentation in the interior basin, all domes have been deprived of the motivation for movement regardless of whether they have gone through the extrusion stage or not, or whether there is additional salt in the pillow beneath them or not.

In addition to the volume of the salt in the pillow stage, and the history of unroofing, other factors may control the history of diapiric growth. These include the geometry of the salt pillow, and whether the salt in the pillow moves into the dome equally from all sides. The pattern and rapidity of subsequent sedimentation may also affect domal growth, either inhibiting or accelerating it. In short, each dome appears to have an individual character and to have followed a distinctive pattern of growth.

2.2.7 CANDIDATE DOMES: Of the seven candidate domes, all but Rayburn's are buried by significant thickness of overlying sediments. In east Texas and north Louisiana, these beds are Eocene in age. In south Mississippi, they are Miocene in age. Burial depth ranges from a maximum exceeding 335 meters (1,100 ft) at Cypress Creek Dome to a minimum of 38 meters (125 ft) at Keechi Dome (excepting Rayburn's). Faulting superjacent to the dome is documented in all domes but Cypress Creek and Lampton; however, absence there may result from a lack of adequate information.

Oakwood, Cypress Creek, Rayburn's, and Richton Domes contain overhangs. Richton, Vacherie, and Keechi, listed in order of decreasing size, are tapered and elongated. Rayburn's is tapered and nearly circular. Lampton is similar, but with a deeper bulge.

As previously discussed, Cypress Creek Dome has what may be the most prominent rim syncline, the Perry Basin. Moderate rim synclines occur at Richton, Vacherie, Oakwood, and Rayburn's Domes and, to a lesser degree, at Lampton Dome. No distinct rim syncline is present at Keechi Dome.

2.2.8 EVIDENCE OF STABILITY: Cessation of regional sedimentation in the Gulf Interior Region has eliminated the mechanism for salt dome movement. This occurred over 40 million years ago in the Eocene in east Texas and north Louisiana and at least 10 million years ago in the Miocene in south Mississippi.

Subsequent history of the area has been one of intermittent erosion and deposition of stream deposits, while the main depositional regime migrated gulfward beneath coastal waters and offshore. The stream-laid Citronelle-Willis may have blanketed the entire area in the Plio-Pleistocene over one million years ago, but it is not preserved in inland areas such as east Texas and north Louisiana. In south Mississippi, it is partially preserved as the Upland Terrace, but the original depositional surface has generally been modified by erosion so that it does not provide a reference plane to permit detection of domal movement or lack of it.

Entrenchment of drainage systems occurred during the Pleistocene because of sea level fluctuations produced by glacial cycles. The intermittently formed floodplains are now perched as terraces within the stream valleys. Where domes are traversed by such valleys, the presence of such terraces provides an opportunity to determine whether warping of terrace surfaces has occurred from domal movement.

Vacherie Dome in north Louisiana, traversed by Bashaway Creek and its two terraces, has provided the best example for the use of terraces to indicate domal stability, as discussed by Kolb in the LSU reports (Martinez and others, 1975, 1976, and 1977).

Richton Dome in south Mississippi is flanked by Thompson Creek on the east and by Bogue Homo Creek on the west, each with three matching terraces. Although Paulson and others (1980) have noted a slight flattening of the terraces opposite the dome, they are otherwise concordant within and between the two valleys. Pine Branch Creek Valley, which heads in the southern half of the dome, similarly contains concordant terraces.

Stream valleys and associated terraces also traverse Oakwood Dome in east Texas, Rayburn's Dome in north Louisiana, and Cypress Creek Dome in south Mississippi. However, the terraces are either too poorly preserved or insufficiently mapped to provide data on dome stability at this time. Other domes, such as Keechi Dome in east Texas, and Lampton Dome in south Mississippi, are overlain by interfluves. Terraces are not available for study in these domal areas.

Although the evidence for domal stability is not absolute, no convincing evidence for domal instability has been cited.

2.3 INTERNAL STRUCTURE OF SALT DOMES

The purpose of this section is to summarize the state of knowledge regarding the composition and internal structure of the salt stocks that form the core of diapiric structures. The report was designed, with the guidance of Dr. Donald H. Kupfer, to apply specifically to the seven candidate salt domes in the salt basins of the Interior Gulf Coastal Plain. Descriptions of the internal structure of two other domes exposed by salt mining operations, Winnfield and Grand Saline, are included in Sections 2.4.1.1 and 2.4.2.1.

The geologic aspects of salt domes have been studied in detail for more than a century. Remarkable quantities of geophysical and well data from the Gulf of Mexico, its bordering inland areas, and other parts of the world have provided the basis for modern interpretation of the nature, ages, origin, shapes, sizes, and emplacement mechanics of the salt domes (Atwater and Forman, 1959; Trusheim, 1960; Halbouty, 1967, 1979a and b; Mattox, 1968; Braunstein and O'Brien, 1968; Kehle, 1978b; the Northern Ohio Geological Society, 1960, 1963, 1970, 1977, 1980).

Salt was originally deposited in flat-lying beds as it precipitated from evaporating saline waters. A majority of the modern salt deposits still form in this way (Johnson and Gonzales, 1978). In the Gulf Coastal Province of the United States, both onshore and offshore, the bedded salt was buried beneath thick sequences of sediments which were subsequently pierced by the salt during the formation of over 500 salt diapirs. In the process of diapirism the salt was contorted into complex

structural configurations. The total structural feature, including the salt pillar and the surrounding sediments, is the salt dome. The central core is called the salt stock, and retains some of the original properties of the deposit, such as bedding, lithologic sequence, and two-dimensional continuity. In the process of intruding the overlying sediments, however, the originally bedded salt acquires new properties, the most important of which are structural complexity, vertical continuity, and overall homogeneity. Increased purity is an important effect of salt diapirism. Portions of the surrounding beds, notably clay, carbonate, and anhydrite, are selectively sorted and discarded (left behind) at first to a minor extent but with increasing efficiency as diapirism proceeds over a long period of time.

The special properties of diapiric salt have been studied for years, particularly in Europe. Such studies have been greatly intensified during the past decade as a result of the potential use of salt domes in the waste isolation program, the strategic petroleum reserve storage program, and the offshore oil-port programs. Reference is made to the earlier reports of Balk (1949, 1953), Muehlberger (1959, 1960), Kupfer (1962, 1970, 1974), Kupfer and others (1976), and Hoy and others (1962) for details. The theoretical modeling studies of Escher and Kuenen (1929) are also particularly informative.

Important recent contributions are either in preparation, in limited distribution, or in less accessible form. Most have been prepared under the auspices of the U. S. Department of Energy. Noteworthy contributions include the Environmental Impact

Statements for Weeks Island and Cote Blanche (Federal Energy Administration, 1977a and b; Acres American, 1977; Golden Associates, 1977), waste isolation studies from the Oak Ridge National Laboratories and Battelle Memorial Institute, reports by Louisiana State University's Institute for Environmental Studies (Martinez and others, 1976, 1977, 1978), and Law Engineering Testing Company (1978f, 1979a) internal reports.

Physical properties of diapiric salt significant to waste isolation are purity, impermeability, mobility and vertical continuity, each of which will be discussed briefly. Much of this information comes from areas other than the Interior Salt Dome Basins of the Gulf Coast. Therefore, these properties must be considered for, and adapted to, domes in these basins. In some cases the physical properties of salt vary from province to province. However, the substantive composition of all Interior Salt Dome Basin domes is similar in essential properties.

2.3.1 PROPERTIES OF THE SALT: The salt stock consists of granular aggregates of halite (sodium chloride) crystals that average 6.3 to 12.7 mm (0.25 to 0.50 in) in diameter and constitute 90 to 99 percent of the mass. Coarse halite crystals, ranging from 25.4 mm (1 in) to several meters in length, are also common. The remainder of the mass is primarily anhydrite (calcium sulfate), which occurs as disseminated grains in the salt (0.5 to 10 percent by volume) or as pure chunks which appear to represent disjointed original bedding (boudinage). For example, large anhydrite chunks are common in portions of the Cypress Creek salt

core. A few of the layered chunks are up to 0.3 meter (1 ft) long. In some places the anhydrite is brecciated and mixed with the salt (flowage-mixing). Minute amounts of various other chemicals may occur (Bloomberg and Landenburg, 1959), but none appear to have any significance for waste storage. The remarkable purity of diapiric salt is one of the most attractive features for waste storage. Detailed descriptions of various salt compositions and textures are contained in Balk (1949), Muehlberger and Clabaugh (1968), Nance and Wilcox (1979) and Cavan and Fuerst (1980).

2.3.1.1 Texture: The texture of salt is generally uniform, and medium-grained (6 to 12 mm (0.25 to 0.50 in)). Some local zones are reported to vary from fine-grained (3.1 mm (0.125 in)) to extremely fine-grained. For example, petrographic analysis of the Cypress Creek salt core revealed the crystals in some sections averaged only 5 mm (0.20 in), with some crystals as small as 0.5 mm (0.02 in). The ultracoarse or megacrystalline areas may be of diverse origin; some authors cite original beds of very pure halite (Muehlberger, 1968), while others cite the presence of liquids or gases that allow coarse recrystallization. Coarsely crystalline salt is a characteristic of most anomalous zones. The consensus among petrographers is that the presence of very coarse-grain salt suggests that no salt movement has occurred since recrystallization; therefore, it is considered an indicator of domal stability.

Fabric analysis (Balk, 1953; Muehlberger and Clabaugh, 1968) indicates a strong vertical elongation of the salt crystals in many areas; the individual grains are like vertically oriented spindles. This vertical elongation is assumed to indicate vertical salt flowage, such as is known to occur during diapirism. Examinations of the cores show that deformed halite is common and that many crystals are elongated and essentially parallel to the vertical axis of the core.

2.3.1.2 Layering: Domal salt is generally layered in dark and light bands, probably relict bedding (Kupfer, 1970). Individual layers can be traced for 305 meters (1,000 ft) in the salt domes of the Interior Salt Basins of the U.S. Gulf Coast (Muehlberger, 1968; Law Engineering, 1979a and b) and in the domes of Germany and Great Britain (Richter-Bernburg, 1975). Thicknesses range from thin laminae to layers several feet thick, but most are from 25 to 254 mm (1 to 10 in). Layered anhydrite is common in the salt cores from Cypress Creek, Oakwood, and Richton Domes. These bands are generally oriented vertically, at less than 25 degrees from the vertical axis of the core, except at Oakwood Dome where some lower dips are common (Cavan and Fuerst, 1980). The cores range in color from whitish-gray to dark gray, the darkening generally being related to increased anhydrite content. The lighter beds average less than one percent calcium sulfate and the darker ones 4 to 20 percent. Layers of pure anhydrite, intensely boudinaged (appearing like sausage links), from 6 to 12 mm (0.25 to 0.50 in) thick represent original, though altered, anhydrite beds in the salt.

2.3.1.3 Stratigraphy: As in any sedimentary section, the stratigraphy of domal salt changes laterally and vertically from place to place. The variable properties are purity, bed thickness, texture, chemical composition, friability, hardness, and structure. However, these are minor physical changes; the salt product of a mine ordinarily varies within very narrow physical and chemical limits. In the domes of the Gulf Coast, differences in the chemical composition of the salt are generally less significant than in other provinces and probably indicate a corresponding uniformity in the composition of the source beds in the Louann Salt. The greatest contrasts in composition in the Gulf Coast, however, are noted between the pure salt from the mines of southern Louisiana and the less-pure salt in cores from the Interior Salt Basins. Each variation is assumed to be more or less typical of the province.

2.3.1.4 Permeability and Porosity: Permeability of domal salt in its undisturbed state is so low that it cannot be measured (Acres American, 1977; Golden Associates, 1977). Mines are reported to have remained open for many years without flooding despite the presence of a water body on the supradomal surface. Salt mobility is a contributing factor to the impermeability of salt. At relatively low temperatures and pressures the salt creeps, filling any voids that might tend to form. Indeed, the only porosity found in salt bodies is that held open by liquids or highly compressed gases, the origins and distribution of which are not completely known. However, both porosity and

permeability are commonly developed at the interface of the salt and caprock as well as at the salt and the external sheath, and recent studies (Martinez and others, 1976, 1977, 1978, 1979, and 1980) indicate that gas and water are present only in trace amounts.

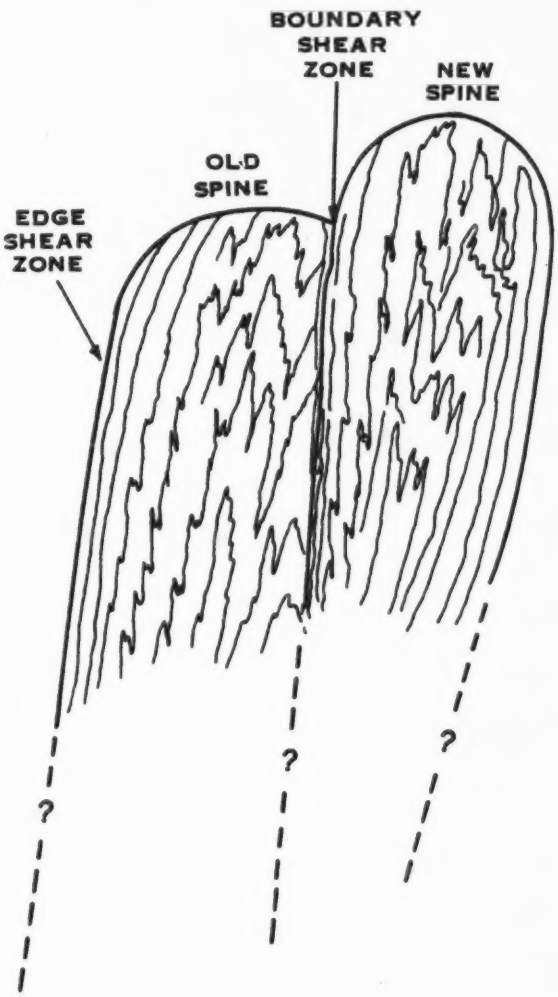
2.3.2 STRUCTURE: The internal structures of salt stocks fall into two categories: (1) typical or normal structures occurring throughout the stock in various stages of development, and (2) abnormal or anomalous structures occurring only in narrow vertical zones. Intense folding is the dominant internally visible structure in a salt stock, while homoclinal shear zones are less commonplace. Anomalous zones of diverse character and origin are described in Section 2.3.3.

2.3.2.1 Folding: Throughout most of the salt stock, the layers are folded around nearly vertical axes. The folds appear to have been formed by both shear and plastic flow. These structures range from broad, open folds to tight, isoclinal folds. In many places, especially in southern Louisiana, there is evidence of refolding of previous folds (Kupfer, 1968). The folds range in size from a few inches to a thousand or more feet across. A common occurrence is the development of small drag folds on the limbs of large folds, which in turn appear to be developed on still larger folds. In some mines which have been opened at two or more levels, the folds have been observed to preserve their general shape and vertical plunge from level to level.

2.3.2.2 Verticality: The vertically oriented texture (elongated grains or crystals) and structure of domal salt, and the generally vertical attitude of the layers and folds have been described and are schematically shown in Figure 2-7. The verticality of both small and large structures in salt domes is significant to the design and construction of mine shafts and corridors.

2.3.3 ANOMALOUS ZONES: An anomalous zone in a salt stock is any zone in which a group of features (compositional, textural, or structural) is observed which is not typical of the normal salt of the stock. The most easily observed and recognizable anomalous features are inclusions of solids, liquids, and gases, but other features may also occur. An anomalous zone is defined as a vertical, tabular portion of the salt stock which incorporates a significant number of these anomalous features. Thus, if several such features occur together, most of the others are likely to occur in the immediate vicinity. It has been observed that most anomalous zones are about 0.6 to 9 meters (2 to 30 ft) wide, extend in a relatively straight alignment for distances of at least 46 to 91 meters (150 to 300 ft) and commonly occur across the entire salt stock (Kupfer, 1980a).

The origin of anomalous zones is controversial and probably varied. The importance of these zones to this study is that most significant problems encountered in salt stocks are confined to these zones, which can be recognized before they are penetrated. Problems and their detection are separate considerations.



GEOLOGY FROM KUPFER, 1968

PREPARED [illegible] DATE [illegible]	NATIONAL WASTE TERMINAL STORAGE PROGRAM GEOLOGIC EVALUATION GULF COAST SALT DOMES	CROSS SECTION SHOWING SPINES AND BOUNDARY SHEAR ZONES
REVISED ____ DATE ____		
REVISED ____ DATE ____		
APPROVED [illegible] DATE [illegible]	LAW ENGINEERING TESTING COMPANY MARIETTA GEORGIA	JOB NO. MV9600 FIGURE 2-7
T-1463-1		

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Most anomalous zones are probably what Kupfer (1976) has termed as boundary shear zones, which are zones that form the boundary between a spine of salt and the outside of the salt dome (external sheath zone), or between two spines (internal boundary zones) as shown in Figure 2-7. Kupfer (1980b) now recognizes that boundary zones can be subdivided, with some parts strongly sheared, other parts containing liquids or gases, and the core commonly containing sediment inclusions. Some anomalous zones are not boundary zones but represent foreign materials that were deposited with the salt beds and subsequently brought up with the salt to their present position.

The common problems associated with anomalous zones, in addition to the obvious impurity of the salt in such areas, are leaks, slabbing, and blowouts. Most leak problems are associated with the external salt-sheath zones, which completely encase the salt stock. These zones are commonly 91 meters (300 ft) and may be thicker over the top of the stock, especially if it is near the surface. This is the zone in which an expansion of the salt has taken place, with consequent increased porosity and permeability. Slabbing is the process of exfoliation of large slabs of salt into the mine workings from the ceiling or walls. It can occur in any part of the mine but is more commonplace in the impure salt of the anomalous zone. The occurrence of slabbing is essentially a problem of rock mechanics that probably can be controlled if the properties of the adjacent salt are properly analyzed and interpreted. Gaseous outbursts that may occur at

the time of blasting are called blowouts, and as far as is known, they are completely confined to anomalous zones.

Detection of an anomalous zone is accomplished by the recognition of several of the various features of the zone. Each of the features can be detected by one or more means such as drilling, geophysics (radar, seismic, resistivity), chemical analyses, or textural and structural studies. Some of the features such as excessive shearing (a true shear zone) commonly are penetrated before the more troublesome features, namely, inclusions and blowouts, are encountered. Thus, geophysical studies suggest the presence of anomalies, core drilling helps to confirm them, and detailed mapping of the advancing mined space may provide a clear warning if the zone has not been recognized previously.

2.3.4 INTERIOR SALT DOMES: Compared to the domes of the Gulf Coast Region in the U. S. and those of Germany, definitive data bearing on the nature of the salt in the domes of the Interior Salt Basins are sparse. Only two small mines (within Grand Saline and Winnfield Domes) occur in the Interior Salt Basins and, especially in Louisiana and Mississippi, oil and other mineral exploration around these domes has been minimal. In order to expand the knowledge of salt and salt domes, five core holes were drilled into the stocks by LSU/IES and LETCo, one each into Vacherie, Rayburn's, Cypress Creek, Richton, and Oakwood Domes.

Studies of the two mines and the five cores have given a partial picture of the nature of the salt. It is interesting to

note that the observational data tend to confirm the prior geological suppositions about them. Geologically, it appears that the interior domes are intermediate in their evolutionary development and growth stages (age, depth, shape) compared to the better known domes of northern Germany and of the Gulf and Atlantic Coastal Provinces of the United States (Tables 2-3 and 2-4).

The salt stocks of the Interior Salt Basins do not appear to have risen as high, as recently, as straight vertically, or as completely as those of the Coastal Salt Basins. However, they are younger, more developed and taller than those of northern Germany. Accordingly, it is possible to predict some of the properties of the salt bodies such as purity and verticality. These predictions are based on limited data and appear to have been confirmed by the interpretation of the recently obtained core hole data.

The evolutionary sequence supports some generalizations about the interior domes. For example, because spines adjacent to anomalous zones occur in salt domes in Germany and in the Lower Gulf Coast, it is reasonable to assume that they also exist in the interior salt stocks. The extent of their occurrence, however, is not known. Similarly, the character of the folding and the amount of sedimentary inclusions that may occur in the salt stocks of the Interior Salt Dome Basins can also be predicted to be intermediate between the extremes of salt stock conditions in domes of Germany and those of Louisiana and Texas.

TABLE 2-3.
GEOLOGIC ASPECTS OF DOMES IN THE INTERIOR AND GULF COASTAL SALT BASINS IN THE U.S., AND THOSE OF NORTHERN GERMANY

Aspect	Germany	Interior	Coastal
Height of top of dome above mother salt horizon	1,500-6,000 meters (5,000-20,000 ft)	5,000-8,000 meters (18,000) 26,000 ft)	12,000-18,000 meters (40,000-60,000 ft)
Age of the salt	Permian	Jurassic	Jurassic
Time of pillow formation	Triassic-Early Jurassic	Jurassic	Unknown
Time of maximum growth	Jurassic to Lower Cretaceous	Upper Jurassic to Late Tertiary	Middle Tertiary
Cessation of movement	Cretaceous to Pre-Oligocene	Oligocene to Miocene	Pleistocene to Recent (some still active)
Diapiric shape	Low Sloping diapirs	Circular to Elongated vertical stocks	Vertical stovepipes, some possible teardrop at depth

TABLE 2-4
APPROXIMATIONS OF GEOLOGIC CONDITIONS IN THE SALT STOCKS OF THE INTERIOR AND GULF COASTAL SALT BASINS IN THE U.S., AND THOSE OF NOTHERN GERMANY

Geologic Properties	German Salt Domes	Gulf Coast Salt Domes	Lower Gulf Salt Domes
Average dip of salt in the stocks	60° - 80°	80° - 85°	85° - 88°
Range of dips commonly observed	40° - 90°	45° - 90°	80° - 90°
Original contemporaneous sediment interbedded in salt	All lithologic types common, dominate the deposit	May be rare	May be rare
Purity of the total salt stock	Overall very impure - as low as 40%	70% - 90%	97% - 99%
Purity of the salt layers in the stock	90% - 95%	90% - 99%	98% - 99.5%
Degree of folding	Simple, open, easily mappable, very little distortion	Moderate, open to closed, some small scale drag folds	Highly complex, interfolding and refolding common

2.4 DESCRIPTION OF MINES IN SALT DOMES OF THE GULF INTERIOR REGION

Winnfield and Grand Saline Salt Domes are the only domes of the Interior Salt Basins containing mined openings in which studies have been made describing the internal structure of salt domes. This section describes the internal structure of these two well-documented domes and mining-related instabilities which occurred at the Carey Salt Mine in Winnfield Salt Dome, as described by Dr. William R. Muehlberger (1979). An understanding of Grand Saline and Winnfield Salt Domes is important in order to understand the internal structure of other domes for which there is only sparse information.

2.4.1 GRAND SALINE SALT DOME, VAN ZANDT COUNTY, TEXAS: Surface expression in the form of a saline marsh led to the early discovery of the Grand Saline Salt Dome in the 1800's. Solution mining of salt began around the turn of the century in the northern section of the dome (Figure 2-8). The Kleer Mine room and pillar mining operations began in Grand Saline Dome in the fall of 1931 with the opening of a shaft in the south-central portion of the dome. The mine has been developed on two levels, 56 and 109 meters (185 ft and 359 ft), respectively, below sea level, with rooms that are 8 to 23 meters (25 to 75 ft) high. The Kleer Mine is relatively problem-free, with no reports of blowouts, oil and gas seeps, serious ceiling slabbing, or spalling of the walls.

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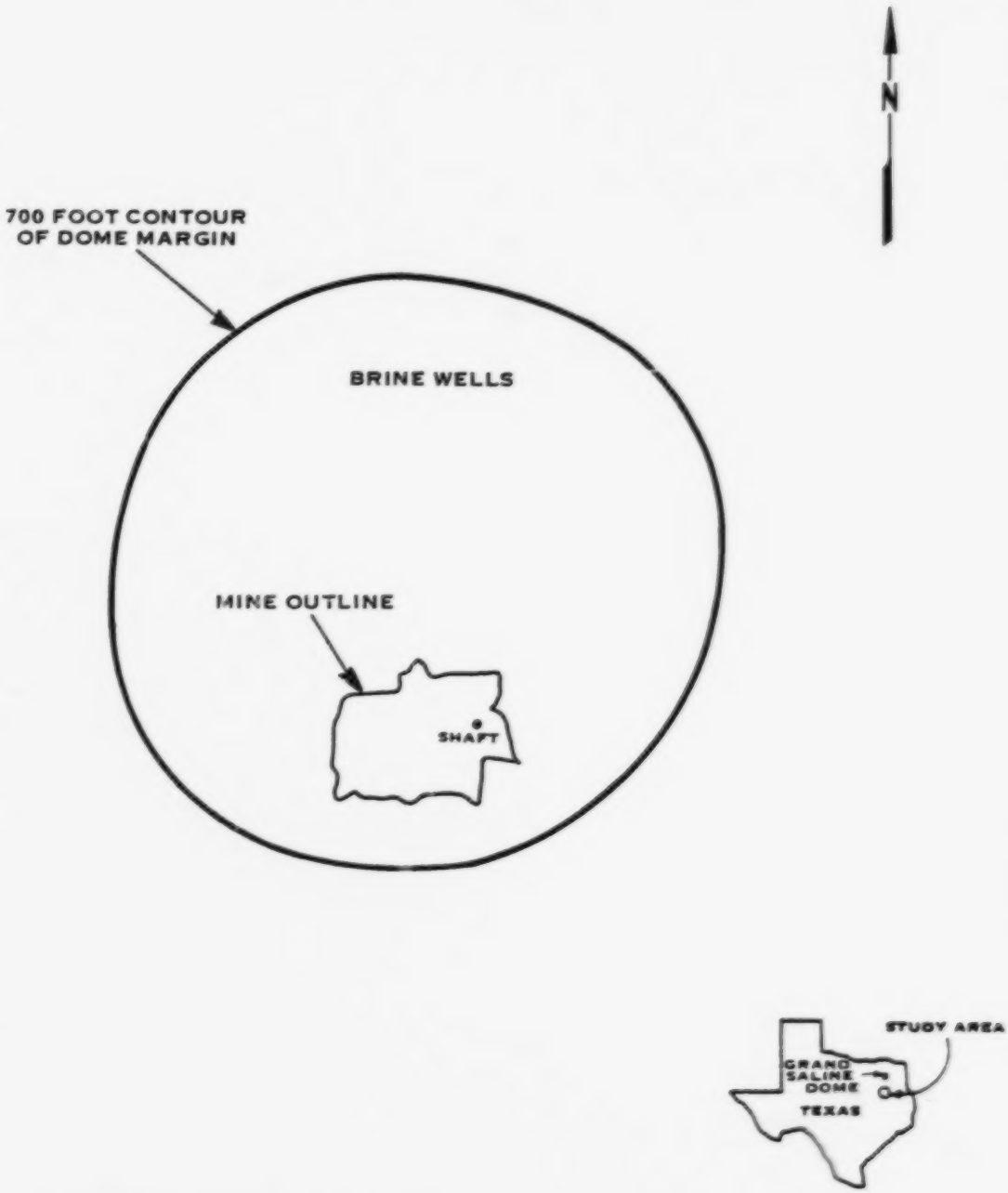

MODIFIED FROM MUEHLBERGER, AND OTHERS, 1962

PREPARED — DATE 1/20/82	NATIONAL WASTE TERMINAL STORAGE PROGRAM GEOLOGIC EVALUATION GULF COAST SALT DOMES LAW ENGINEERING TESTING COMPANY MARIETTA GEORGIA	GRAND SALINE SALT DOME KLEER SALT MINE LOCATION
REVISED — DATE		
REVISED — DATE		
APPROVED — DATE 1/22/82		JOB NO. MV9600 FIGURE 2-8
T-1306-1		

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2.4.1.1 Structure Exposed in the Salt Mine: Typical vertical bands of alternate dark and light layers of uniform thickness are observed in Kleer Mine. The banding is the result of chemically graded bedding produced from the gradual evaporation of sea water and successive precipitation of more soluble salts in a closed basin (Muehlberger and Clabaugh, 1968). The bands grade from the dark, anydrite-rich layers at the bottom to light, almost pure salt layers at the top. The presence of the banding makes it possible to trace for long distances the large and sometimes complex folds exposed in the mine walls (Figure 2-9). Shear folding, which is the most common structural feature of the mine, was observed in which only the dark bands were sheared. This feature indicates that under stress the dark anhydrite had resisted movement and had been broken while the intra-bedded area of rock salt had been recrystallized.

Mining was discontinued in the southeast portion of Kleer Mine when several sylvite-rich layers were encountered. Sylvite occurs in layers, generally a few inches thick, that are commonly grouped to form bands from 0.3 to 0.6 meters (1 to 2 ft) thick. These bands contained five percent sylvite in a dominantly halite sequence. The presence of sylvite is believed to indicate that the mine face was approaching the edge of the salt dome. The uppermost beds of the Louann sequence are composed of sylvite and other potash-rich minerals, the most soluble mineral salts commonly found in sea water. According to an interpretation of the significance of anomalous areas encountered in salt mining, these uppermost beds moved into the lateral borders of the upward

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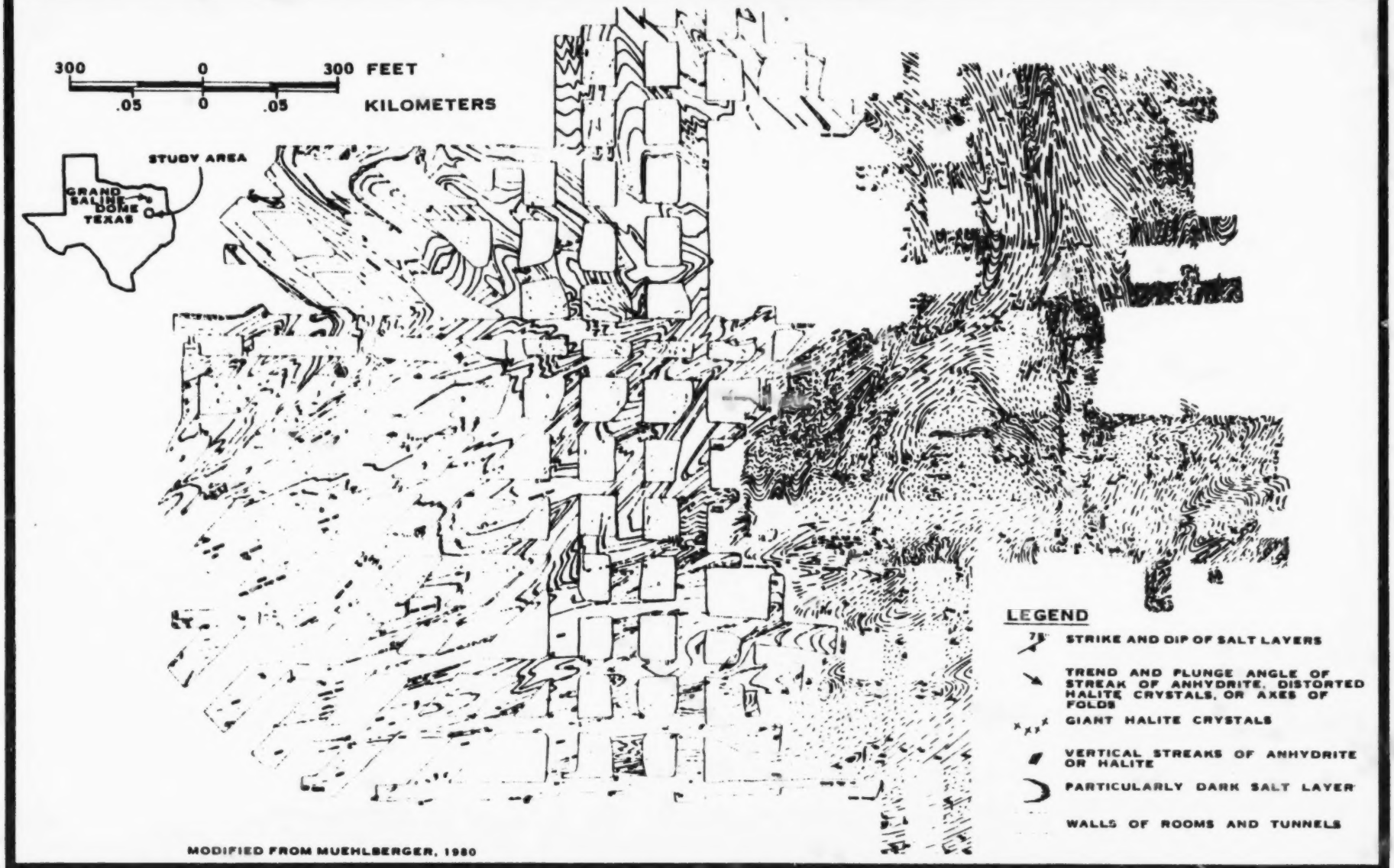
300 0 300 FEET
.05 0 .05 KILOMETERS
STUDY AREA
GRAND SALINE DOME TEXAS
MODIFIED FROM MUEHLBERGER, 1980
LEGEND
STRIKE AND DIP OF SALT LAYERS
TREND AND PLUNGE ANGLE OF STREAK OF ANHYDRITE, DISTORTED HALITE CRYSTALS, OR AXES OF FOLDS
GIANT HALITE CRYSTALS
VERTICAL STREAKS OF ANHYDRITE OR HALITE
PARTICULARLY DARK SALT LAYER
WALLS OF ROOMS AND TUNNELS

PREPARED		DATE	9-30-83
REVISED		DATE	
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APPROVED		DATE	9-15-80

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NATIONAL WASTE TERMINAL STORAGE PROGRAM
GEOLOGIC EVALUATION GULF COAST SALT DOMES
LAW ENGINEERING TESTING COMPANY
MARIETTA, GEORGIA

GRAND SALINE SALT DOME
SALT STRUCTURE AT
KLEER SALT MINE

JOB NO. MV9600 FIGURE 2-9

FIGURE 2-9

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doming salt and became a part of the salt sheath (Muehlberger, W. R., written communication, 1978).

2.4.1.2 Growth History of Grand Saline Salt Dome: Large salt crystals, commonly 0.3 to 0.9 meter (1 to 3 ft) across the crystal faces, occur in the dome within beds which are bounded by anhydrite-rich layers. The largest crystal which has been identified is about 1 meter (4 ft) wide, 6 meters (20 ft) high and 30 meters (100 ft) long. The size of crystals can be correlated directly with the degree of purity, the larger crystals including the least amount of anhydrite (Muehlberger and Clabaugh, 1968). A petrofabric study of the salt crystals was conducted by Clabaugh (1962) to determine the growth history of the dome. These petrofabric studies show a significant number of salt crystals with similar orientations, indicating that salt movement followed planes parallel to the crystals. Samples taken from various parts of the mine did not have a common orientation, suggesting that the dome experienced differential uplift during emplacement, tending to confirm the theory of alternating spine development as the principal mode of vertical growth. Salt near the dome margin was finer-grained and less consistently oriented than salt farther inside the stock. A higher strain-rate differential near the dome margin could produce these conditions (Muehlberger and Clabaugh, 1968).

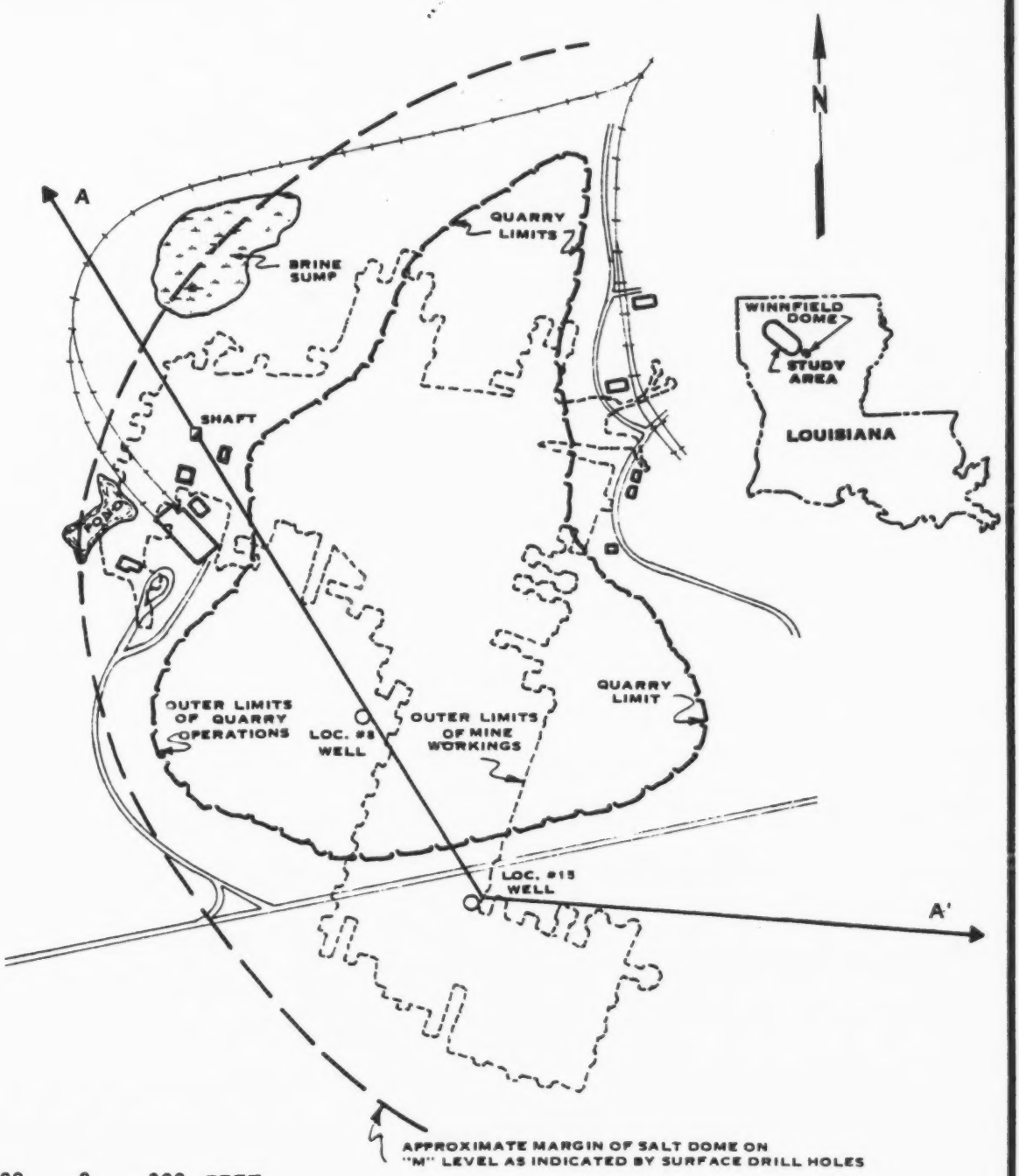
Mapping of the prominent banding by Muehlberger (1959) indicated two lines of discontinuity or changes in fold-trend orientation in two areas of the mine. These lines are approximately

parallel to the regional fault pattern, suggesting that faults in the sedimentary overburden may be related to domal uplift (Muehlberger and Clabaugh, 1968).

2.4.2 WINNFIELD SALT DOME, WINN PARISH, LOUISIANA: The Winnfield Salt Dome is unique in having both a salt mine within it and a surface quarry above it that is removing caprock (Figure 2-10). Additionally, oil exploration over and around its flanks has generated enough data to draw a fairly complete cross-sectional view of the dome (Figure 2-11).

The internal structure of the Winnfield Salt Dome, exposed in the workings of the Carey Salt Mine, was studied by Hoy and others (1962). Petrofabric studies on salt from six localities in the mine were studied by Muehlberger and Clabaugh (1968). Muehlberger and Haenggi in 1980 surveyed a line etched in the western part of the mine during a flood in 1937 in order to analyze deformation within the salt (Figure 2-12).

Hessenbruch (1975) has studied the geology of Winn Parish through use of available well data to determine the timing and sequence of development of the salt structures within the parish. The most prominent development of the structural features occurred in the Late Jurassic (Cotton Valley time), while growth rates slowed throughout the Early Cretaceous (Kupfer and others, 1976). Growth accelerated due to the increased flow of salt into the rising piercement domes (including Winnfield) near the end of the Early Cretaceous and for most domes stopped in the early part of the Late Cretaceous. Winnfield Dome continued to rise during



PREPARED DAH DATE 4-20-83	NATIONAL WASTE TERMINAL STORAGE PROGRAM GEOLOGIC EVALUATION GULF COAST SALT DOMES	WINNFIELD SALT DOME SURFACE AND SUBSURFACE FEATURES AT CAREY SALT MINE
REVISED DATE	LAW ENGINEERING TESTING COMPANY MARIETTA GEORGIA	JOB NO. MV9600 FIGURE 2-10
REVISED DATE		
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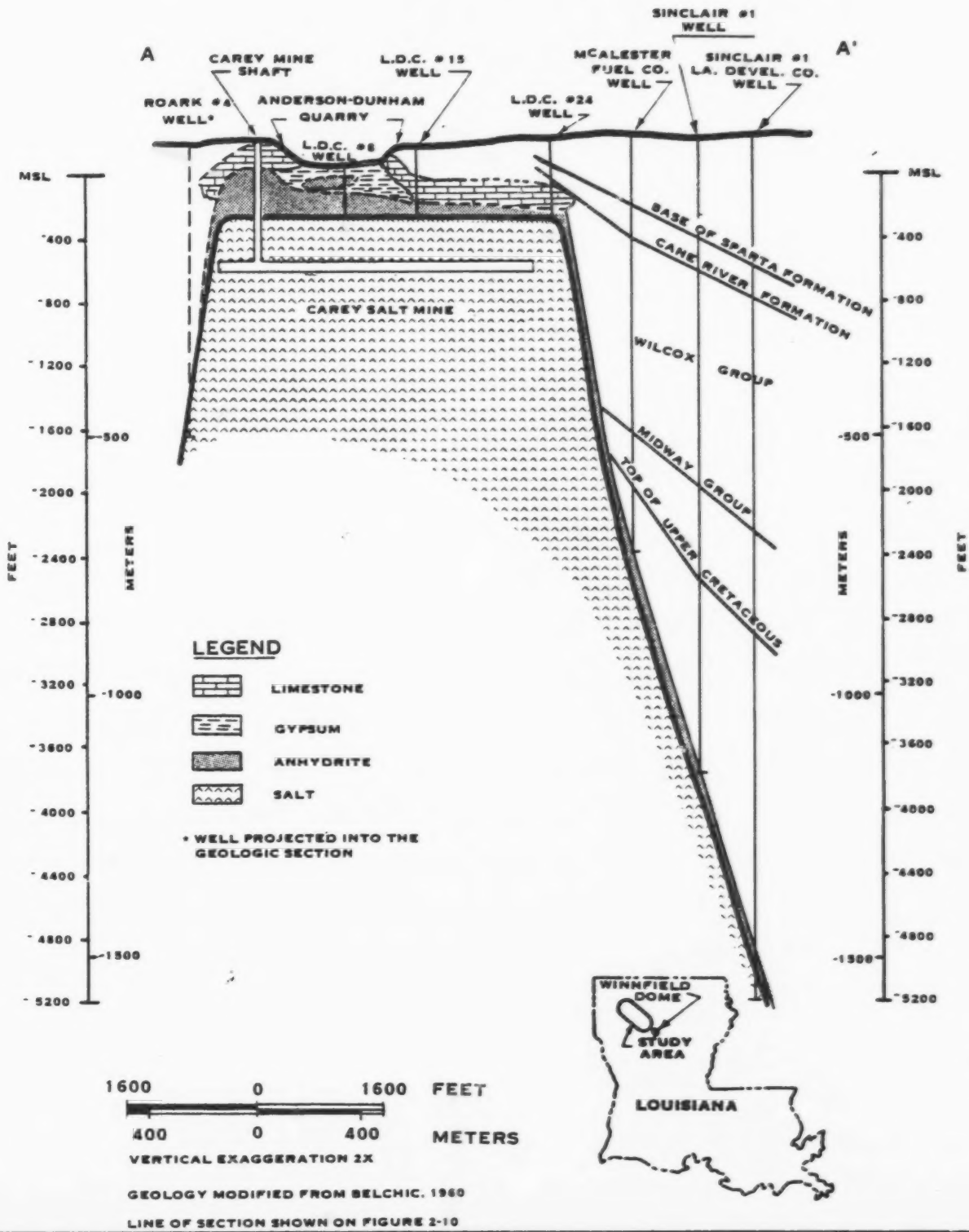

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PREPARED DATE REVISED DATE REVISED DATE APPROVED DATE T-1201-1	NATIONAL WASTE TERMINAL STORAGE PROGRAM GEOLOGIC EVALUATION GULF COAST SALT DOMES LAW ENGINEERING TESTING COMPANY MARIETTA GEORGIA	GEOLOGIC CROSS SECTION THROUGH WINNFIELD SALT DOME JOB NO. MV9600 FIGURE 2-11

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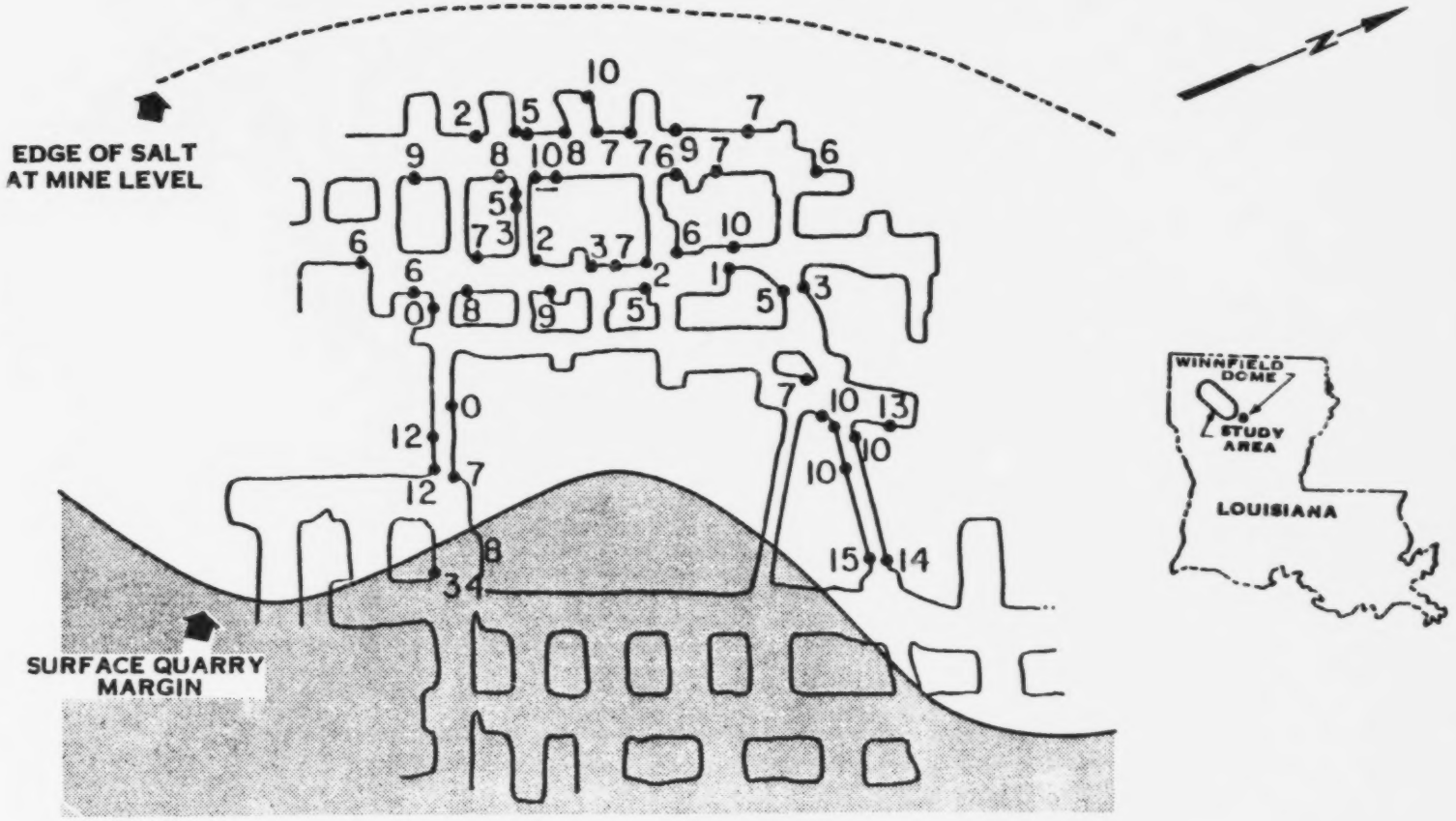

LEGEND

- ELEVATIONS IN HUNDREDTHS OF FEET ABOVE ARBITRARY DATUM ALONG WATER-LEVEL ETCH LINE

200 0 200 FEET
50 0 50 METERS

FROM MUEHLBERGER, 1980

FIGURE 2-12

PREPARED ___ DATE 4-23-82	NATIONAL WASTE TERMINAL STORAGE PROGRAM GEOLOGIC EVALUATION GULF COAST SALT DOMES LAW ENGINEERING TESTING COMPANY MARIETTA, GEORGIA	WINNFIELD SALT DOME DEFORMATION OF WATER-LEVEL ETCH LINE AT CAREY SALT MINE
REVISED ___ DATE ___		
REVISED ___ DATE ___		
APPROVED ___ DATE 9-15-82		
T-1203-1		JOB NO. MV9600 FIGURE 2-12

the early Tertiary, Sparta sand time (Claiborne Group, middle Eocene), resulting in uplifted beds which are tilted away from the dome (Belchic, 1960).

Belchic (1960) provided a detailed summary of exploration and exploitation of the dome. She described the original caprock limestone that formed an escarpment up to 18 meters (60 ft) in height around a central depression partially occupied by a lake. Quarrying in the caprock, successive diversions of drainage, and the growth of spoil dumps have obliterated much of the original modern topography.

In the first years of the quarrying operation, which commenced in 1936, the principal product removed was limestone, which formed the upper layer of the caprock. Since 1951 only anhydrite and gypsum, which were exposed after removal of the limestone, have been quarried.

The salt mine is 247 meters (811 ft) below the collar of the shaft and is overlain by approximately 122 meters (400 ft) of rock salt. Rooms were enlarged from an original 7-meter (22-ft) height to a 18- or 21-meter (60- or 70-ft) height by drilling and blasting.

2.4.2.1 Structure Exposed in the Salt Mine: The presence of anhydrite bands allows an interpretation of the salt structure (Figure 2-13). Large folds have been developed in a simple form similar to the style found in Grand Saline Salt Dome. Layering dips steeply, generally more than 70 degrees. Near the edges of the dome the layers tend to parallel the dome margin. Like layering, fold axes and lineations all dip steeply into the dome,

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GEOLOGY MODIFIED FROM MUEHLBERGER, 1980

PREPARED ___ DATE 4-24- REVISED ___ DATE REVISED ___ DATE APPROVED ___ DATE T-1202-1	NATIONAL WASTE TERMINAL STORAGE PROGRAM GEOLOGIC EVALUATION GULF COAST SALT DOMES LAW ENGINEERING TESTING COMPANY MARIETTA GEORGIA	WINNFIELD SALT DOME STRUCTURE OF SALT ON THE 811-FOOT LEVEL AT CAREY SALT MINE JOB NO. MV9600 FIGURE 2-13

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suggesting that an overhang exists along the west and southwest edges. However, drilling shows the presence of caprock along the side of the dome and very little overhang.

Anhydrite aggregates (pencils) are especially visible near the shaft. The mine was partially flooded in 1937, dissolving the salt from around the nearly vertical anhydrite pencils.

No faults or fractures in the salt have been observed other than those associated with mining or those resulting from gas blowouts.

2.4.2.2 Interstitial Brine and Carbon Dioxide: An unusual feature of this mine is the seepage of brine and carbon dioxide (CO_2) when new excavations are made. Brine-filled, crater-like salt deposits a few inches in diameter are formed by brine bubbling through the floor. Salt stalactites form as brine drips from the ceiling. The flow of brine and gas is largest immediately after excavation, gradually tapering off over a period of several years. This decrease is ascribed to either draining of the cavities or sealing by salt precipitation. Quantitative estimates of flow rates made by Muehlberger in January, 1960 led him to believe that the total quantity was small (a few pools 0.9 to 2 meters (3 to 6 ft) across and under 25 mm (1 in) deep and that flow had virtually ceased.

The carbon dioxide and brine are particularly abundant in the western and southern parts of the mine in areas which are closest to the edge of the dome. Blowouts have occurred in a number of localities where the mine has penetrated closest to the dome edge.

Nine holes in the mine floor in the northwestern part, drilled to an average depth of 183 meters (600 ft), encountered carbon dioxide and brine. Gas and brine flowed from some of the holes under high pressure as described in detail by Belchic (1960).

The largest blowout was in the southernmost part of the mine where approximately 8,400 tonnes (7,500 tons) of salt rubble were exploded from an opening more than 30 meters (100 ft) high. This was also the last time mining operations were extended within a few hundred feet of the dome margin. The material from the blowout contained gas bubbles at pressures estimated to be as much as 50,650 to 101,300 kPa (500 to 1,000 atm) at 0 C (32 F), causing it to crackle when stepped on. The results of the analysis of the gas are given in Table 2-5.

TABLE 2-5.
ANALYSIS OF GAS ENTRAPPED IN SALT AT WINNFIELD DOME

Gas	Composition, Percent	Gas	Composition, Percent
CO_2	46.9	H_2	1.8
H_2O	17.3	CH_4	1.5
N_2	18.4	A	0.4
CO	4.8	C_2H_2	0.4
O_2	4.4	Other Hydrocarbons	0.4
SO_2	3.7		

Hoy and others (1962) suggest that carbon dioxide contained in the salt has been responsible for the blowouts. They also point out the proximity of the blowouts to the boundary of the salt dome. Figure 2-13 shows the location of the blowouts

relative to the approximate border of the salt dome at the level of the mine; all are within 91 meters (300 ft) of the dome wall. Kuhn (in Hoy and Kuhn, 1964) argues, by analogy with carbon dioxide explosions in the Werra Region, Germany, that the carbon dioxide was formed by basaltic intrusions that heated limestone at depth. The presence of such basaltic intrusions has yet to be demonstrated in association with Gulf Coast salt structures.

2.4.2.3 Brittle Failure: Muehlberger reported from his visit to the mine in January, 1960, that in the northeast part of the mine large slabs about 152 mm (6 in) thick had fallen from the ceiling and spalls had broken from the walls. Some of these slabs had salt stalagmites growing on them and stalactites above them, indicating the presence of small amounts of brine that drained after slab failure. These fallen slabs are in the area where coupled and decoupled explosions, using from 9 to 907 kg (20 to 2,000 lb) of chemical explosives, were made in cavities and in drill holes up to 30 meters (100 ft) below the mine floor. These explosions were made for Project Cowboy* between December, 1959 and March, 1960 (Adams and Allen, 1961) and, thus, cannot be used as evidence of catastrophic failure of the rooms of a normal, working salt mine.

2.4.2.4 Mine Floods: Flooding of the mine occurred on July 4, 1937. The flooding was the result of a plug failure in the main

* Atomic Energy Commission experiments concerning the feasibility of seismic decoupling by explosions in underground cavities.

shaft after workmen had attempted repair. The plug failed after all personnel had left the mine so that, undetected, the water poured in continuously over the long July 4th holiday, causing the mine to be closed down for pumping-out. Only the northwest part of the mine was open at that time and, consequently, only that portion was flooded.

The etch line which resulted from the 1937 flooding was mapped by Muehlberger (1980), and is shown in Figure 2-12. It shows the deviation of the water line in hundredths of feet from an arbitrary zero elevation. No systematic deformation can be seen in the main area of the map. However, a major upward deflection is seen along the eastern edge of the mapped area. This up-warped area also coincides with that part of the mine that underlies the surface quarry. This suggests the possibility that the removal of the caprock (as much as 46 to 61 meters (150 to 200 ft) of overburden and rock) caused the salt to expand upward to fill the newly created void. No originally horizontal datum for the main part of the mine was available for surveying to test this hypothesis. The subsequent closing of the mine has made further study impossible, except by indirect observations from the surface. Careful repetitive leveling across the dome and quarry could check this hypothesis.

On November 17 and 18, 1965, over 30 years after the first flood, the Carey Salt Mine (Winnfield Dome) was again flooded. The available information has been used to construct the following sequence of events which resulted in the flooding of the mine (Martinez and Wilcox, 1976).

Although known as a wet mine, the Carey Salt Mine had, during the intervening years, accumulated no more than small amounts of water in a shaft sump due to condensation from pumped-in humid air. However, a few weeks before mid-November the sump was observed to have accumulated increasing amounts of water which required more frequent pumping. The increase prompted a search for the source and, after several days, the discovery of a new 102-mm (4-in) jet of water was found in an abandoned room on the night of November 17th. Personnel were evacuated and the mine was flooded within 2 days. The mine is still flooded.

During the period of flooding, evidence of subsidence (about 127 mm (5 in)) of the caprock was observed at the ground surface. In addition, all holes drilled over the years from the ground surface into the salt lost circulation at about 122 meters (400 ft), presumably at the caprock/salt contact.

For a period of 2-1/2 years following the 1965 flooding of the mine, a quarry in the caprock was dry except for minor surface drainage. Thereafter, it was necessary to resume pumping water from the quarry at a preflooding rate of 38 l/sec (600 gal/min).

The interpretation of observers (Martinez and Wilcox, 1976) regarding these events is that the source of the flood water is seepage from the surface which accumulated in a cavernous zone at the caprock/salt contact, and that from there the water filtered downward through about 122 meters (400 ft) of salt to the mine. Other observers (Muehlberger, 1979; Kupfer, 1980a) suggest that the movement of water from the top of the salt to the mine might

have been through fractures developed as a result of shaft installation (1931) and blasting incident to mining operations (1932-1965), and possibly from Atomic Energy Commission testing (Operation Cowboy: 1959-1960). Still another observer (Elliott, 1967) speculates that the postulated fracturing was due to collapse of the cavern in the base of the caprock following draining of its water into the mine and flooding.

The generic relationship between a hypothetical fractured zone and human underground activity is suggested by the proximity of the flooding leak to the mine shaft and the mined-out portion of the dome (Figure 2-13), as well as by the sequence of events. Martinez and Wilcox (1976) further reason that the flooding drained enough water from the cavernous zone to require 2-1/2 years to refill it and to keep the quarry essentially dry. A rough calculation of the volume of the mined-out space compared to the assumed volume of water required to fill the caprock cavern tends to confirm the above interpretation. The reestablishment of the original drainage patterns by 1968 suggests that the extremely rapid circulation caused by the flooding had ceased. This would indicate the temporary, and possibly even permanent, preservation of the containment integrity of the dome below the mine level.

2.5 OVERVIEW OF INTERIOR SALT BASIN SEISMICITY

This section describes methodology and summarizes the results of the regional seismic risk analysis of the Gulf Coast Region. Drs. H. James Dorman and Leland T. Long provided assistance in its preparation.

The analysis consisted of three main parts described in detail in the following sections: (1) historic seismicity, (2) regions of similar seismic risk, and (3) ground motions for surface facilities and probable accelerations at depths of 610 to 914 meters (2,000 to 3,000 ft).

The historic seismicity and maximum earthquakes were determined for the areas surrounding the candidate domes. There are no correlations between earthquake epicenters and known specific tectonic features within the study region. The concept of seismotectonic regions, discussed in detail below, was utilized to define areas of comparable seismic risk. It was established that ground accelerations will not exceed 0.06g at the surface of a repository site in the Gulf Coast Region or one-third that value at repository depths.

2.5.1 SEISMOTECTONIC REGIONS APPROACH TO SEISMIC RISK ANALYSIS:

Except for the New Madrid earthquake series (1811-1812), surface displacement during historic earthquakes has not occurred in the south central United States. Furthermore, the earthquakes of the Interior Salt Basins are not known to be associated with specific tectonic structures. In the absence of plate boundaries and identifiable active tectonic structures within or near the

region surrounding the candidate salt domes, a regional approximation of seismic risk was utilized. Earthquake epicenters that cannot be reasonably correlated with specific tectonic features are identified with the "seismotectonic" regions in which they occur.

The delineation of seismotectonic regions is based on regional similarities of tectonic framework, geologic history, crustal structure, and historic seismicity. Criteria used to delineate the seismotectonic regions include:

(1) Crustal thickness and composition

(2) Stress regime

(3) Gravity and magnetic fields

(4) Heat flow

(5) Surface and subsurface geological characteristics.

The seismotectonic regions defined on these criteria for the south central United States are:

(1) Interior Salt Basin

(2) Gulf Coast

(3) Central Texas

(4) Ouachita

(5) Wichita-Arbuckle

(6) New Madrid Fault Zone

(7) Central Stable Region.

Table 2-6 details the criteria used to delineate these seismotectonic regions which are shown in Figure 2-14. Table 2-7 presents the Modified Mercalli (MM) intensity scale.

Table 2-6. Geologic Characteristics of the Seismotectonic Regions

SEISMOTECTONIC REGION	SURFACE GEOLOGY	GRAVITY (Mgal)	CRUSTAL THICKNESS (Km)	HEAT FLOW (°F/100')	EARTHQUAKES (No. of Events <IV MMI) (Max MMI Events) (Years of Record)
Interior Salt Basin	Cenozoic and Quaternary sediments on Paleozoic and/or continental basement rock.	30 to -20 avg: 0	30 - 35	1.4 - 2.1 mode: 1.65	9 VI (Rusk, TX, 1891)* 88
Gulf Coast	Cenozoic and Quaternary sedimentary deposits on transitional or oceanic basement rock.	30 to -50 avg: -20	10 - 30	1.2 - 2.0 mode: 1.4	5 VI (Donaldsonville, La. 1930) 65
Central Texas	Mesozoic sedimentary rocks on Precambrian basement rocks.	-10 to -140 avg: -80	40 - 45	0.8 - 1.8 mode: 1.2	4 V (W. Texas, 1966) 62
Ouachita	Folded Paleozoic sedimentary rocks, often buried by later deposits.	20 to -100 avg: 0	30 - 50+	1.2 - 2.0 mode: 1.6	20 VII (Texas, 1882) 161
Wichita-Arbuckle	Paleozoic and Precambrian rocks intruded by Mesozoic intrusives.	30 to -140 avg: -50		1.0 - 1.8 mode: 1.3	23 VII (El Reno, Okla., 1952) 59
New Madrid Faulted Zone	Faulted Mesozoic and Paleozoic sedimentary platform deposits on Precambrian basement.	20 to -20 avg: 0	40 - 50	1.2 - 2.0 mode: 1.5	113 XII (New Madrid, Mo., 1811-12) 168
Central Stable	Mesozoic and Paleozoic sedimentary platform deposits on Precambrian basement.	60 to -200 avg: -60	40 - 50	0.8 - 2.2 mode: 1.55	21 VII (Kansas, 1867, 1906; Okla. 1956) 168

*Probably a tornado

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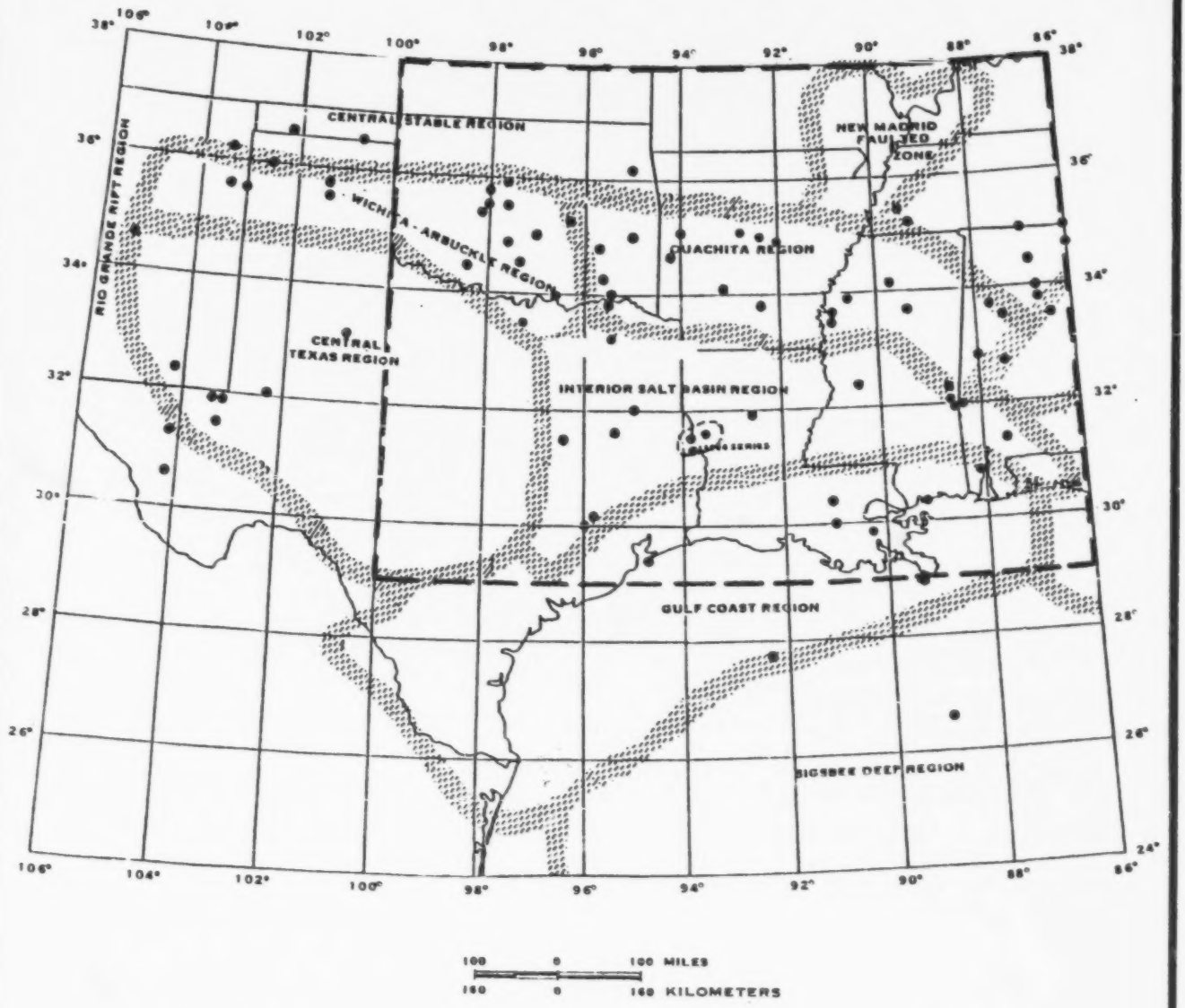

THE EPICENTERS PLOTTED CORRESPOND TO EVENTS WITH INTENSITY IV-V OR GREATER MODIFIED MERCALLI INTENSITY SCALE. FOR ALL EVENTS, SEE APPENDIX G, TABLE I

EPICENTERS WITHIN NEW MADRID FAULT ZONE HAVE NOT BEEN PLOTTED DUE TO HIGH DENSITY SPACING AND SCALE LIMITATIONS.

LEGEND

REGION BOUNDARY ZONES

EARTHQUAKE EPICENTERS (ONE OR MORE EVENTS)

BOUNDARY OF REGION DISCUSSED IN TABLE 2-6

PREPARED ____ DATE ____ REVISED ____ DATE ____ REVISED ____ DATE ____ APPROVED ____ DATE ____ T-1176-2	NATIONAL WASTE TERMINAL STORAGE PROGRAM GEOLOGIC EVALUATION GULF COAST SALT DOMES LAW ENGINEERING TESTING COMPANY MARIETTA GEORGIA	SEISMO-TECTONIC REGIONS OF THE SOUTH CENTRAL U. S. A. JOB NO. MV 9600 FIGURE 2-14

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TABLE 2-7.
MODIFIED MERCALLI INTENSITY SCALE OF 1931
(ABRIDGED) (WOOD AND NEWMANN, 1931)

I. Not felt except by a very few under especially favorable circumstances.

II. Felt only by a few persons at rest, especially on upper floors of buildings. Delicately suspended objects may swing.

III. Felt quite noticeably indoors, especially on upper floors of buildings, but many people do not recognize it as an earthquake. Standing motorcars may rock slightly. Vibration like passing of truck. Duration estimated.

IV. During the day felt indoors by many, outdoors by few. At night some awakened. Dishes, windows, doors disturbed; walls make creaking sound. Sensation like heavy truck striking building. Standing motorcars rocked noticeably.

V. Felt by nearly everyone, many awakened. Some dishes, windows, etc., broken; a few instances of cracked plaster; unstable objects overturned. Disturbance of trees, poles and other tall objects sometimes noticed. Pendulum clocks may stop.

VI. Felt by all, many frightened and run outdoors. Some heavy furniture moved; a few instances of fallen plaster or damaged chimneys.

VII. Everybody runs outdoors. Damage negligible in buildings of good design and construction; slight to moderate in well-built ordinary structures; considerable in poorly built or badly designed structures; some chimneys broken. Noticed by persons driving motorcars.

VIII. Damage slight in specially designed structures; considerable in ordinary substantial buildings with partial collapse; great in poorly built structures. Panel walls thrown out of frame structures. Fall of chimneys, factory stacks, columns, monuments, walls. Heavy furniture overturned. Sand and mud ejected in small amounts. Changes in well water. Persons driving motorcars disturbed.

IX. Damage considerable in specially designed structures; well-designed frame structures thrown out of plumb; great in substantial buildings, with partial collapse. Buildings shifted off foundations. Ground cracked conspicuously. Underground pipes broken.

X. Some well-built wooden structures destroyed; most masonry and frame structures destroyed with foundations; ground badly cracked. Rails bent. Landslides considerable from riverbanks and steep slopes. Shifted sand and mud. Water splashed (slopped) over banks.

XI. Few, if any, (masonry) structures remain standing. Bridges destroyed. Broad fissures in ground. Underground pipelines completely out of service. Earth slumps and land slips in soft ground. Rails bent greatly.

XII. Damage total. Waves seen on ground surfaces. Lines of sight and level distorted. Objects thrown upward into air.

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Seismotectonic regional boundaries are approximate and transitional rather than distinct and may be several kilometers in width. The established boundaries may be revised by incorporation of new information or with better understanding of existing data. They are not always delineated by obvious geologic or geophysical features.

Historic seismicity data or information on all reported earthquakes with an epicentral intensity of IV-V MM or greater, occurring between latitudes 29° to 38°N and longitudes 86° to 100°W, have been assembled from historic sources and are recorded in the Appendix. These data were compared with the seismotectonic regions of the southcentral United States. The number of earthquakes of each intensity level within each seismotectonic region defines the characteristic seismicity for each region, as shown in Table 2-8.

The historic seismicity data were inspected for instances in which reported events may have been the result of human activity. It has been shown that human activity is capable of generating earthquakes by the creation of reservoirs and by explosions, as well as by the extraction and injection of fluids in the earth (Bardwell, 1970; Carder, 1970; Evans, 1970; Munson, 1970; and Scopel, 1970). All south central U. S. earthquakes were compared to former and existing oil and gas producing areas to determine if fluid injection or withdrawal could be responsible for triggering the shocks. In each state some earthquakes were found to be suspect. Additionally, two reported earthquakes were deleted

TABLE 2-8.
TABULATION OF SEISMIC EVENTS

Seismo-Tectonic Region	Historic Record (Years)	Number of Events of Given Intensity									
		IV-V	V	V-VI	VI	VI-VIII	VII	VIII	IX	X	XI	XII
Interior Salt Basins	88	1	7		1							
Gulf Coast	65	1	3	1								
Central Texas	62		4									
Ouachita	161	1	14	1	3		1					
New Madrid	168	14	56	2	27	2	6	1	2	3		
Wichita-Arbuckle	61		12		10		1					
Central Stable Region	112	1	16		1		3					
Total Number of Events		18	112	4	42	2	11	1	2	3		

from the historic earthquake data because they proved to be in the category of explosion-generated ground motion.

The concept of a seismotectonic region involves the assumption of uniform seismicity within the region, i.e., stresses in these areas continuing to be concentrated and released in the same characteristic manner. For the purpose of seismic risk evaluation, it is also assumed that the maximum historical earthquake reported for a specific seismotectonic region will not be

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exceeded in the future; also, this maximum earthquake can occur at any geographic location within a given seismotectonic region with equal probability.

The geographic pattern of historic seismicity (see Figure 2-14) indicates that there are localized areas where more earthquakes occur than elsewhere. To some seismologists this suggests that the maximum earthquake for that province has a greater likelihood of occurring in these local seismic areas. However, the available data are not sufficient to subdivide these areas precisely. Thus, the seismotectonic regions used for earthquake frequency calculations are, in effect, a state-of-the-art approach to seismic risk determination.

The individual seismotectonic regions defined within the southcentral United States are briefly discussed below.

2.5.1.1 Interior Salt Basin Region: The Interior Salt Basin Seismotectonic Region is the area south of the Gulf Coast Basin boundary fault system and north of the Angelina-Caldwell Flexure in Texas and Louisiana and the Wiggins Uplift in Mississippi. The Interior Salt Basin Region contains three major salt dome basins (Mississippi, North Louisiana, and East Texas). Other major structures include the Sabine and Monroe Uplifts. The region is tectonically stable and is currently in an emergent, erosional cycle.

The seismicity of the region is low. Only nine earthquakes with epicentral intensities exceeding IV MM have been reported in the area during the past 88 years. The largest event to occur in

the region was the controversial January 7, 1891 event at Rusk, Texas, with an epicentral intensity conservatively evaluated at VI MM. Geologists have questioned if an earthquake actually occurred at Rusk on January 7, 1891, and, if one occurred, its intensity. The historical record reports violent weather at the time, so it is possible that damage attributed to an earthquake may actually have been the result of a tornado.

2.5.1.2 Gulf Coast Region: The Gulf Coast Seismotectonic Region is the area north of the Sigsbee Deep in the central Gulf of Mexico. Major structures include the South Louisiana, South Texas, and Houston Embayments. The offshore portion of the region is undergoing slow subsidence due to sedimentation and is characterized by active growth faults. The growth faults do not extend to the basement rock and they do not generate earthquakes because the displacement occurs as creep, which affords a continual release of stress.

The seismicity of the Gulf Coast Region is low, and no correlations can be made between epicenters and individual geologic structure. Five earthquakes exhibiting epicentral intensities in excess of IV MM have occurred in the region during the past 65 years. The largest event was the intensity VI MM Donaldsonville, Louisiana earthquake of October 19, 1930. It was felt over an area of 46,620 km^2 (18,000 mi^2). An isoseismal map of this earthquake is shown in Figure 2-15.

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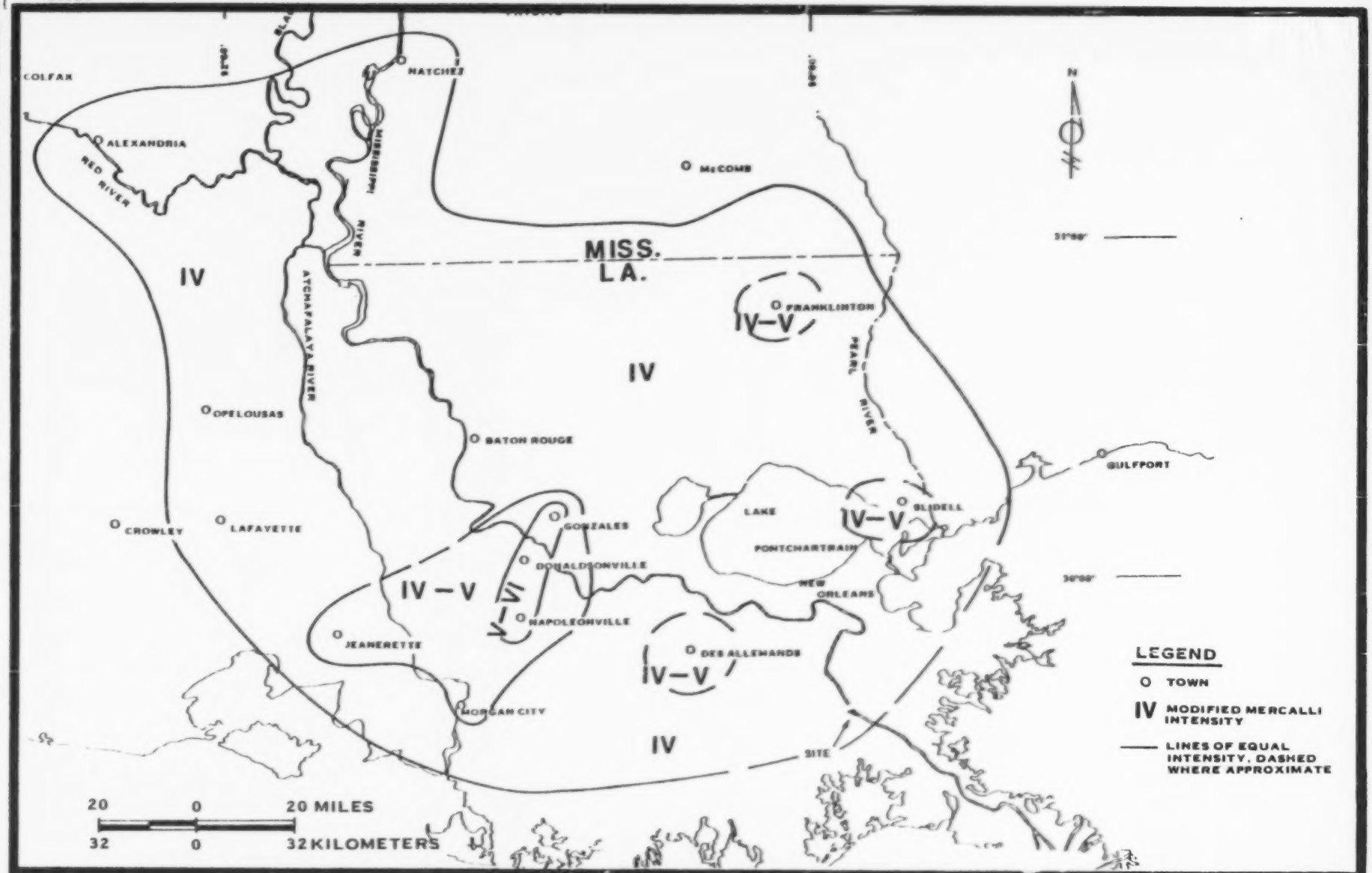

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NATIONAL WASTE TERMINAL STORAGE PROGRAM
GEOLOGIC EVALUATION GULF COAST SALT DOMES
LAW ENGINEERING TESTING COMPANY
MARIETTA, GEORGIA

AREAS OF SIMILAR INTENSITY FOR THE DONALDSONVILLE EARTHQUAKE OCTOBER 19, 1930

JOB NO. MV9600 FIGURE 2-15

FIGURE 2-15

2.5.1.3 Central Texas Region: The Central Texas Seismotectonic Region is the area south of the Wichita-Arbuckle Uplift, east of the Rio Grande Rift Zone, and west of the Mexia-Talco (boundary) Fault Zone. Major structures include the Llano Uplift, the Permian Basin, and several other broad basins and arches. The Central Texas Region is a tectonically stable platform area. All of the surface faults within the region are considered inactive.

Seismicity of the region is low. Only five earthquakes exhibiting epicentral intensities in excess of IV MM have occurred in the region during the past 62 years. The largest historic earthquake of the Central Texas Seismotectonic Region occurred near Kermit, in western Texas, on April 26, 1977 and exhibited epicentral intensity V MM.

2.5.1.4 Ouachita Region: The Ouachita Seismotectonic Region is a belt of deformed rocks south of the Central Stable Region, north of the boundary fault system and east of the Arbuckle Mountains. The Ouachita Region is an orogenic belt composed of several over-thrust sheets of tightly folded, metamorphosed Paleozoic sediments. The region is tectonically stable, as evidenced by the fact that the mountainous section is undergoing erosion.

The Ouachita Trend is thought to extend eastward beneath the Coastal Plain or the Mississippi Embayment, into the folded Appalachian Mountains. This regional trend has numerous surface and subsurface faults; however, the faults have not been directly correlated to earthquakes. The comparison of earthquake epicenters shows that earthquakes have been widely distributed

throughout the region. Since the causative mechanisms of earthquakes in this region are not well understood, all the folded areas within the Ouachita Region are arbitrarily considered to have equal potential for earthquake occurrence.

Seismicity of the Ouachita Region is considerably higher than in the bordering regions to the south. During the 161-year period of historical records, 20 earthquakes exceeding epicentral intensity IV MM have occurred in the region. The largest earthquake in the Ouachita Seismotectonic Region was the 1882 Arkansas event reported to have been felt over an area of 349,650 km^2 (135,000 mi^2). Epicentral intensity for this earthquake was VII MM.

2.5.1.5 Wichita-Arbuckle Region: The Wichita-Arbuckle Seismotectonic Region is the area south of the Central Stable Region, north of the Central Texas Region and west of the Ouachita Region. Major structures within the Region include the Wichita Uplift, the Arbuckle Mountains, the Anadarko Basin and the Muenster Arch. The region is tectonically stable and currently undergoing an erosional phase. None of the fault zones show evidence of surface displacements during historic earthquakes.

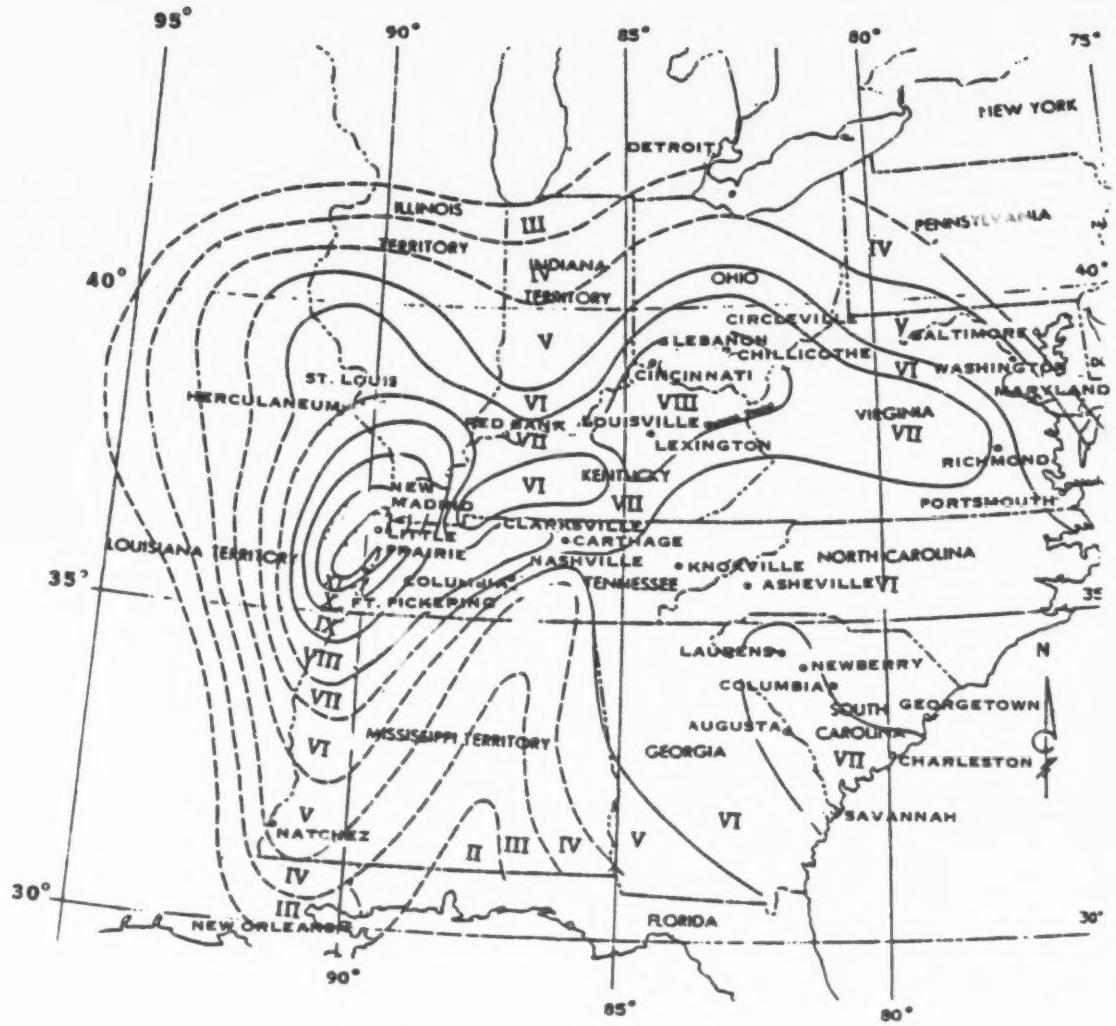
The seismicity of the Wichita-Arbuckle Seismotectonic Region is similar to that of the Ouachita Seismotectonic Region to the east and is considerably higher than that in the bordering regions to the south. Twenty-three earthquakes with epicentral intensities exceeding IV MM have occurred in the region during

the past 59 years. The largest historic earthquake within the region occurred on April 9, 1952 near El Reno, Oklahoma. This event had an epicentral intensity of VII MM.

2.5.1.6 New Madrid Faulted Zone: The New Madrid Faulted Zone almost coincides with the northern section of the Mississippi Embayment. It is composed of a series of northeast-southwest trending faults that terminate against the north edge of the buried Ouachita Foldbelt. The tectonic stability of the region is uncertain and the area is seismically active. It is known that faults of the region are capable of generating large earthquakes. Although some of the earthquakes in the region appear to be related to the northeast trending faults, the cause of the high level of seismicity is unknown. The New Madrid Faulted Zone is structurally separated from the study area by the Arkoma Basin and the Ouachita Mountains.

During the 168-year historical period, 113 earthquakes exceeding epicentral intensity IV MM have been reported in the New Madrid Faulted Zone. The largest earthquakes in the south central United States occurred near New Madrid, Missouri during 1811-1812 and exhibited epicentral intensities of XII MM. An isoseismal map of the composite effects of these major events is shown in Figure 2-16.

2.5.1.7 Central Stable Region: The Central Stable Seismotectonic Region includes much of the area east of the Rocky Mountains, north of the Wichita-Arbuckle and Ouachita Mountains, and



MODIFIED MERCALLI INTENSITIES

MODIFIED FROM STEARNS AND WILSON, 197

LEGEND

- ○ TOWN
- V. MODIFIED MERCALLI INTENSITY
- —— INTENSITY CONTOUR LINES, DASHED WHERE APPROXIMATE

100 0 100 MILES

150 0 150 KILOMETERS

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NATIONAL WASTE TERMINAL STORAGE PROGRAM
GEOLOGIC EVALUATION GULF COAST SALT DOMES
LAW ENGINEERING TESTING COMPANY
MARIETTA GEORGIA

COMPOSITE ISOSEISMAL MAP OF MAXIMUM EFFECTS OF NEW MADRID, MISSOURI EARTHQUAKE SERIES, 1811 - 1812

JOB NO. MV9600 FIGURE 2-16

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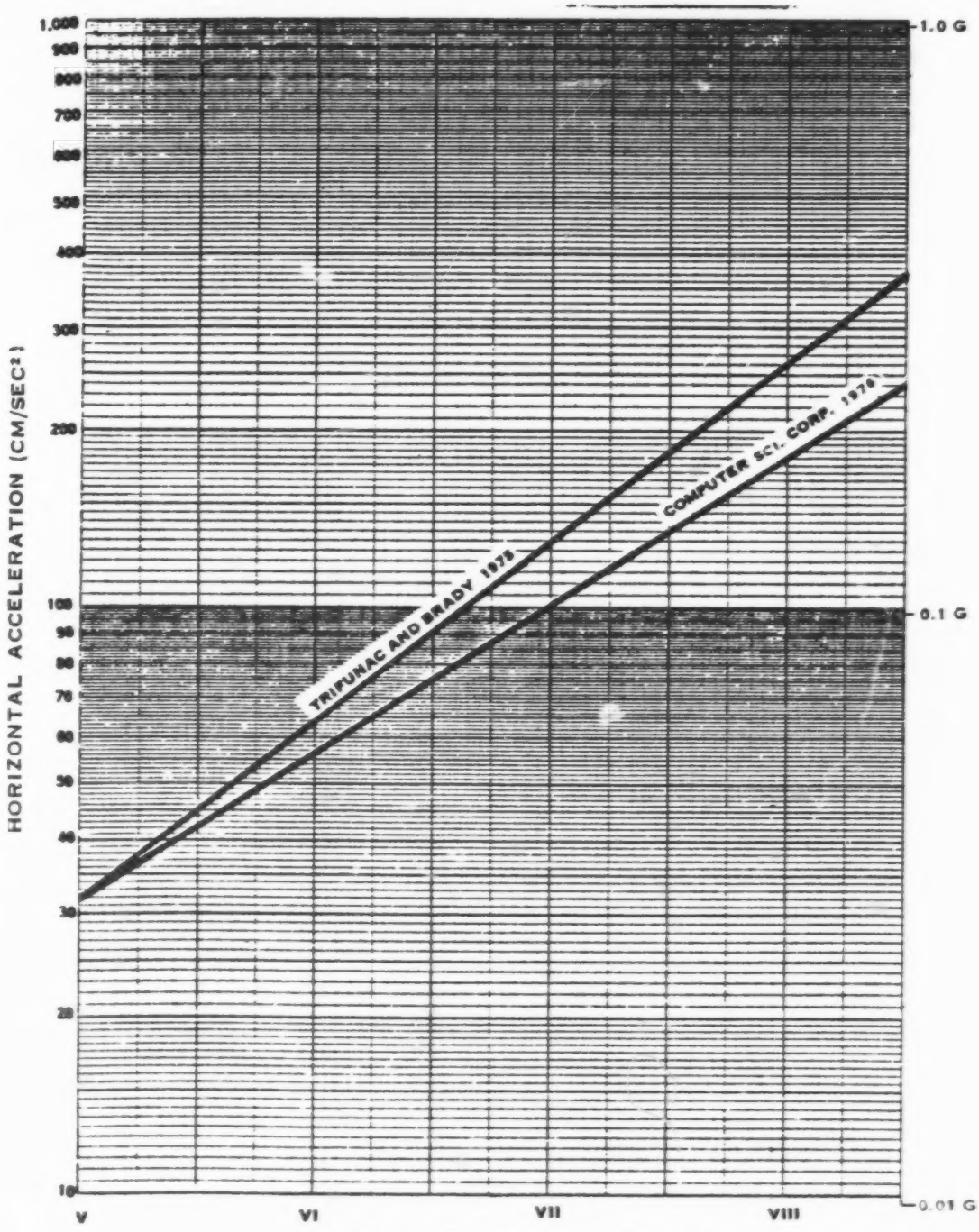
west of the Appalachian Mountains. Major structures include the Ozark Uplift and the Cincinnati Arch. The region is tectonically stable, seismicity is low, and none of the fault zones show surface displacements during historic earthquakes.

During the 168-year historical period, 21 earthquakes exceeding epicentral intensity IV MM have occurred within the Central Stable Region. The largest earthquake of the region to occur within 804 km (500 mi) of a candidate dome was the October 30, 1956 northeastern Oklahoma event. This earthquake exhibited an epicentral intensity of VII MM and was felt over an area of 9,583 km^2 (3,700 mi^2).

2.5.2 EARTHQUAKE RECURRENCE ANALYSIS: The historic earthquake data for the appropriate seismotectonic regions were used to compute Modified Mercalli intensity and acceleration recurrence functions for the study area domes. This was accomplished by determining the distribution of earthquake epicentral intensity, or magnitude per unit time, of each seismotectonic region and then applying an attenuation model for the travel path to the study domes for all points within each seismotectonic region. The summation of the resulting intensities at the candidate domes yields site intensity recurrence functions. The application of an approximate intensity-acceleration relationship, as shown in Figure 2-17, permits probabilistic site acceleration functions to be computed.



1 G = 981 CM/SEC²

PREPARED [illegible] DATE 4-22-80	NATIONAL WASTE TERMINAL STORAGE PROGRAM GEOLOGIC EVALUATION GULF COAST SALT DOMES	SEISMIC STABILITY ANALYSIS RELATIONSHIP BETWEEN EARTHQUAKE INTENSITY AND GROUND ACCELERATION
REVISED ____ DATE ____	LAW ENGINEERING TESTING COMPANY MARIETTA GEORGIA	JOB NO. MV9600 FIGURE 2-17
REVISED ____ DATE ____		
APPROVED [illegible] DATE ____		
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A conservative maximum design earthquake with a horizontal ground acceleration at the surface of 0.06g (intensity VI MM) has been determined to be appropriate for all the candidate domes. This selection was based on a conservative evaluation of the level of ground motion that is statistically predictable, considering seismic and tectonic history and geologic structure. This level of ground motion would be associated with a Modified Mercalli Intensity VI earthquake, the largest regional event recorded within the Interior Salt Basin Region.

2.5.3 RESPONSE OF SOIL AND ROCK STRUCTURES TO DYNAMIC LOADING: As previously discussed, the maximum expected value of peak horizontal acceleration for the Interior Salt Basin Region, 0.06g, has been determined by a probabilistic evaluation of the historical earthquake intensity data and the application of an appropriate intensity-acceleration relationship. However, to fully specify the expected ground motion at candidate domes within the region, site-specific response spectra scaled to the maximum expected acceleration are necessary. Furthermore, the necessity to specify expected ground motion, both at the surface and at depth, requires that representative response spectra be generated for suggested repository depths of 610 to 914 meters (2,000 to 3,000 ft) as well as at the surface.

In the following discussion, methodology used to derive response spectra for the Hainesville Salt Dome in Wood County, Texas will serve as an example for computations at other domes within the Interior Salt Basin Region.

In general, the derivation of response spectra for the candidate salt domes will involve the following aspects:

(1) Determination of a suitable acceleration-time history

(2) Determination of site-specific, soil-profile elastic moduli and damping parameters

(3) Determination of the dynamic interaction between the salt dome and surrounding strata

(4) Generation of response spectra at ground surface and at repository depth by incorporating the resonance characteristics of the soil profile.

This procedure is discussed in the following sections.

2.5.3.1 Analytical Techniques: The site response analyses were performed using the SHAKE computer program (Schnable and others, 1972). The program models earthquake ground motions as shear waves propagating vertically. The SHAKE analysis is capable of accepting an acceleration-time history specified for any point in the soil profile model, and generating time histories at any other points that are compatible with the specified motion. The soil and rock layers are assumed to be uniform, horizontal, and infinite in extent. Values of stress, strain, and rigidity may vary significantly in a particular soil profile. Also, soil damping may be influenced by both strain level and frequency of motion. These conditions are accommodated in the analysis by an iterative procedure. Iteration is continued until shear moduli and damping values are compatible with shear strains. Effective strain levels are assumed to be equal to 0.65 of the maximum

strain, as suggested in Schnable and others (1972), for use in determining shear moduli and damping. The analysis is performed in the frequency domain by using the Fourier Transform.

2.5.3.2 Acceleration Time History: Strong ground-motion data recorded instrumentally are not available for the Interior Salt Basin Region. In the absence of these data, an artificial acceleration-time history, derived from the Nuclear Regulatory Commission Regulatory Guide 1.60 acceleration response objective, was employed in the analysis.

The NRC response spectrum is dominated by high-frequency motions characteristic of sites with hard rock near or at the surface, a condition incompatible with the thick soil profiles present in the Interior Salt Basins Region. These unconsolidated geologic materials attenuate accelerations in the high-frequency range. In addition, the use of the NRC response spectrum to define the surface motion at a candidate dome would significantly underestimate the surface response at periods greater than about 0.7 second. Consequently, it was necessary to utilize SHAKE to produce excitation motions that would satisfy spectral content and acceleration levels appropriate for the study area. This was done by a trial process whereby the Regulatory Guide 1.60 type motions are specified for a rock profile, compatible base motions are computed, and then compatible surface motions for the study area soil profiles are computed. The process was continued until the soil site's maximum acceleration of 0.065g was computed. This

procedure resulted in an artificial acceleration-time history appropriate for the ground surface.

2.5.3.3 Soil Properties: A cross section through the Hainesville Salt Dome is shown in Figure 2-18. The seismic response analysis for a salt dome incorporates the maximum shear modulus (or S-wave velocity at low strain) for each soil or rock stratum in the profile, and the variation of these values with strain level. The values of S-wave velocity at a shear strain of approximately 1×10^{-4} percent are presented in Figure 2-19. The variation of shear modulus (or S-wave velocity) with strain level is dependent on many factors including confining pressure, void ratio, over consolidation pressure, and plasticity characteristics. The variation of shear modulus with strain level was calculated for various depths in the soil profile using equations presented by Hardin and Drnevich (1972).

Values of damping versus strain level were also calculated for sand and clay soils at various depths in the profile and with various void ratios. Zero damping values were assumed in the rock strata.

2.5.3.4 Salt Dome Interaction with Adjacent Strata: The possibility of dynamic interaction between the salt dome and adjacent strata was investigated by analyzing the response of a soil and rock profile adjacent to the dome (Profile A in Figure 2-19) and a profile through the dome (Profile B in Figure 2-19). Each profile was assumed in the analysis to be infinite in horizontal

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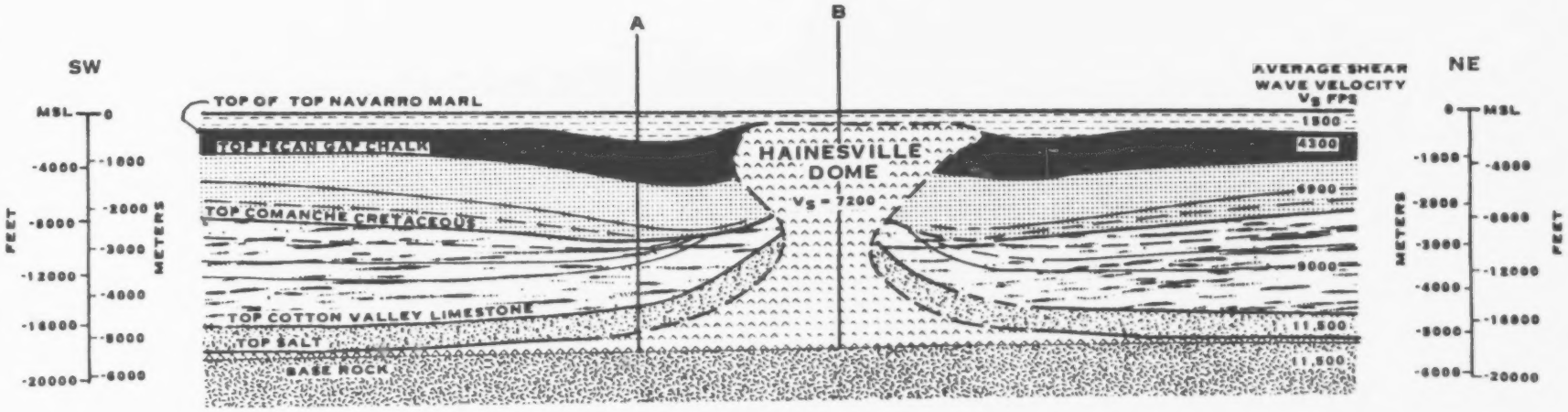

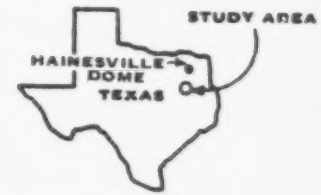

LEGEND

- AVERAGE SHEAR WAVE VELOCITY = 1500 FPS
- AVERAGE SHEAR WAVE VELOCITY = 4300 FPS
- AVERAGE SHEAR WAVE VELOCITY = 6900 FPS
- AVERAGE SHEAR WAVE VELOCITY = 9000 FPS
- AVERAGE SHEAR WAVE VELOCITY = 11,500 FPS
- AVERAGE SHEAR WAVE VELOCITY = 11,500 FPS
- AVERAGE SHEAR WAVE VELOCITY = 7200 FPS (SALT)

SEISMIC ANALYSIS PROFILES

A- PROFILE OF SEDIMENTS ADJACENT TO DOME.

B- PROFILE OF SEDIMENTS AND SALT THROUGH DOME.

2 0 2 MILES

2 0 2 KILOMETERS

FIGURE 2-18

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T-1204-1		JOB NO. MV9600 FIGURE 2-18

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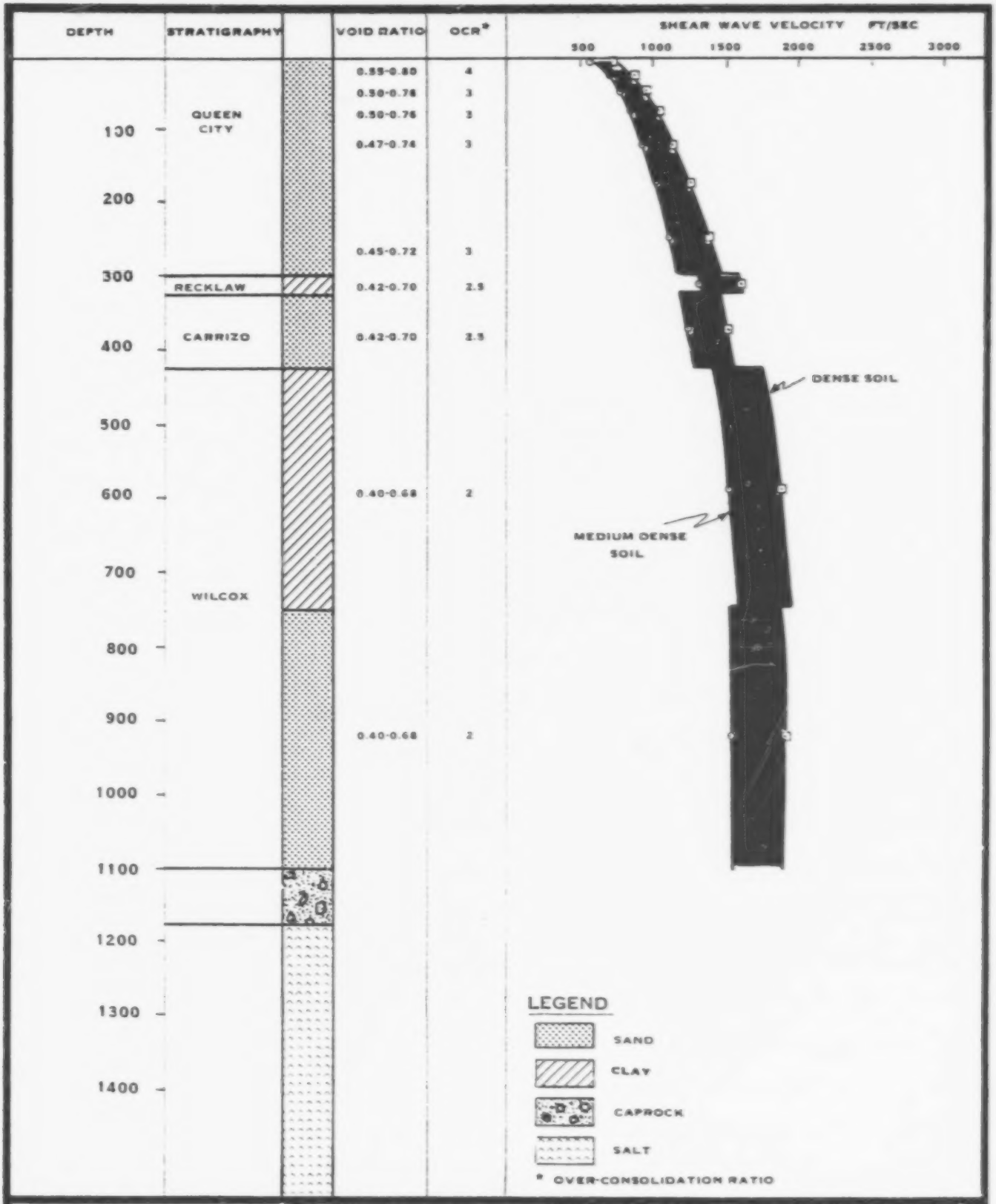

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NATIONAL WASTE TERMINAL STORAGE PROGRAM
GEOLOGIC EVALUATION GULF COAST SALT DOMES
LAW ENGINEERING TESTING COMPANY
MARIETTA GEORGIA

SEISMIC STABILITY ANALYSIS
RELATIONSHIP BETWEEN SHEAR WAVE VELOCITY AND DEPTH

JOB NO MV9600 FIGURE 2-19

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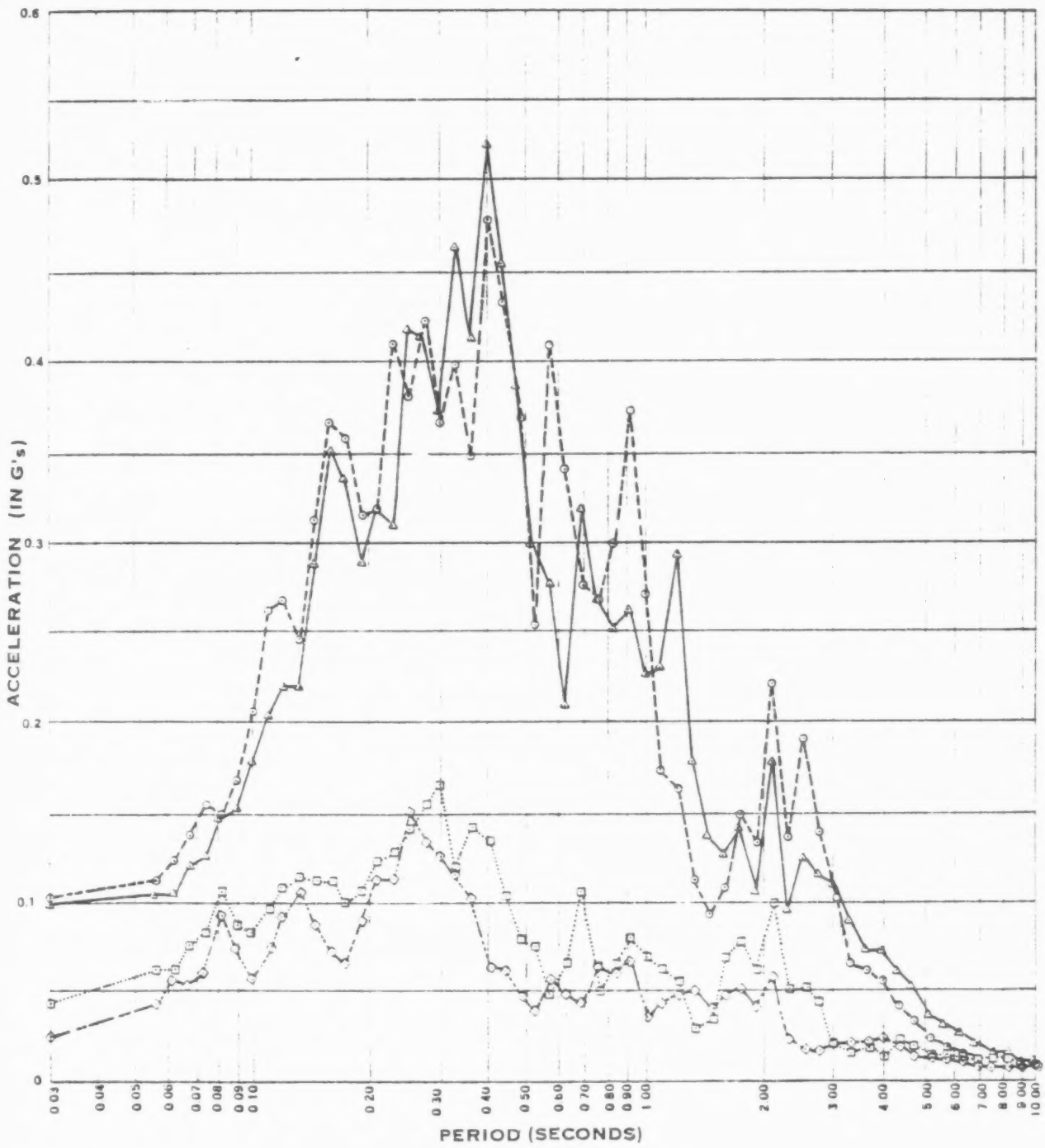
extent. A base depth of 5,669 meters (18,600 ft) was chosen because it resulted in the greatest divergence of surface motion between Profiles A and B. Figure 2-20 presents the corresponding acceleration response spectra for both profiles at the surface and at a depth of 610 meters (2,000 ft).

Figure 2-20 shows that the profiles through the dome and adjacent to the dome respond in a similar manner. Computed displacements for each soil profile are compatible and imply that there is no significant interaction between the salt dome and the surrounding strata. This provides the basis to restrict further analyses to the profile through the dome.

2.5.3.5 Design Response Spectra and Acceleration Levels: A conservative design acceleration of 0.1g was used in the analyses to determine the design response spectra and acceleration levels at the ground surface and at a depth of 610 meters (2,000 ft). This conservative surface acceleration is nearly double the maximum expected acceleration for the study region (0.06g) determined from the probabilistic analysis discussed in Section 2.5.2. These analyses used Profile B through the Hainesville Salt Dome in East Texas. The excitation motion was specified at the top of caprock, 335 meters (1,100 ft) below the surface. Both dense and medium-dense soil conditions were considered.

The resulting surface and repository acceleration-time histories for the dense soil condition, and the response spectra for both soil densities are shown in Figures 2-21 and 2-22, respectively. The acceleration amplification versus depth for



ACCELERATION VALUES NORMALIZED TO 0.1 G FOR PROFILE B AT GROUND SURFACE

LEGEND

- PROFILE A, SURFACE
- PROFILE A, 2000 FEET
- PROFILE B, SURFACE
- PROFILE B, 2000 FEET

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T-1205-1

NATIONAL WASTE TERMINAL STORAGE PROGRAM
GEOLOGIC EVALUATION GULF COAST SALT DOMES
LAW ENGINEERING TESTING COMPANY
MARIETTA GEORGIA

SEISMIC STABILITY ANALYSIS
RESPONSE SPECTRA
ADJACENT AND THROUGH DOME

JOB NO. MV9600 FIGURE 2-20

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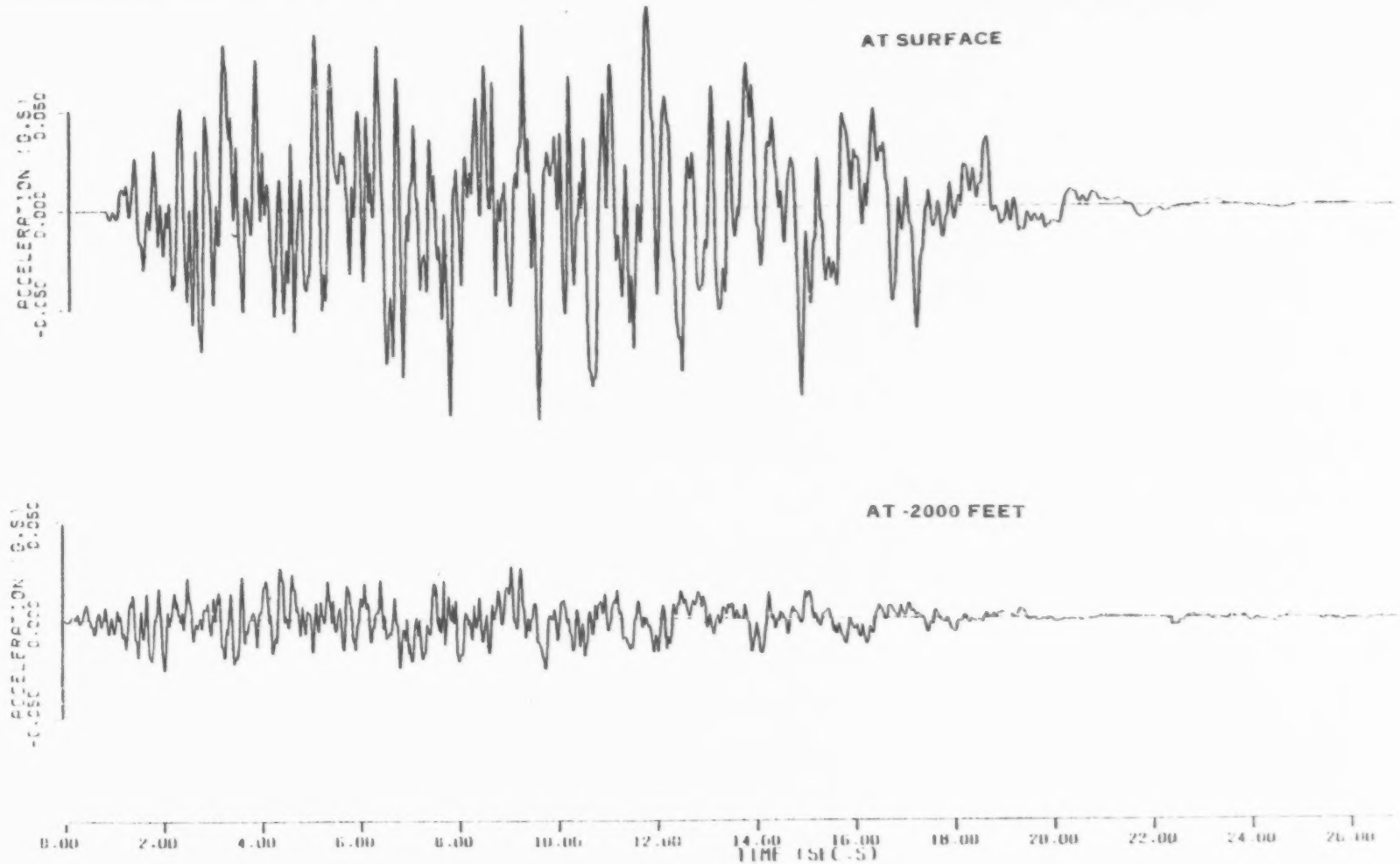

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NATIONAL WASTE TERMINAL STORAGE PROGRAM
GEOLOGIC EVALUATION GULF COAST SALT DOMES
LAW ENGINEERING TESTING COMPANY
MARIETTA, GEORGIA

SEISMIC STABILITY ANALYSIS
ACCELERATION TIME HISTORIES

JOB NO. MV9600 FIGURE 2-21

FIGURE 2-21

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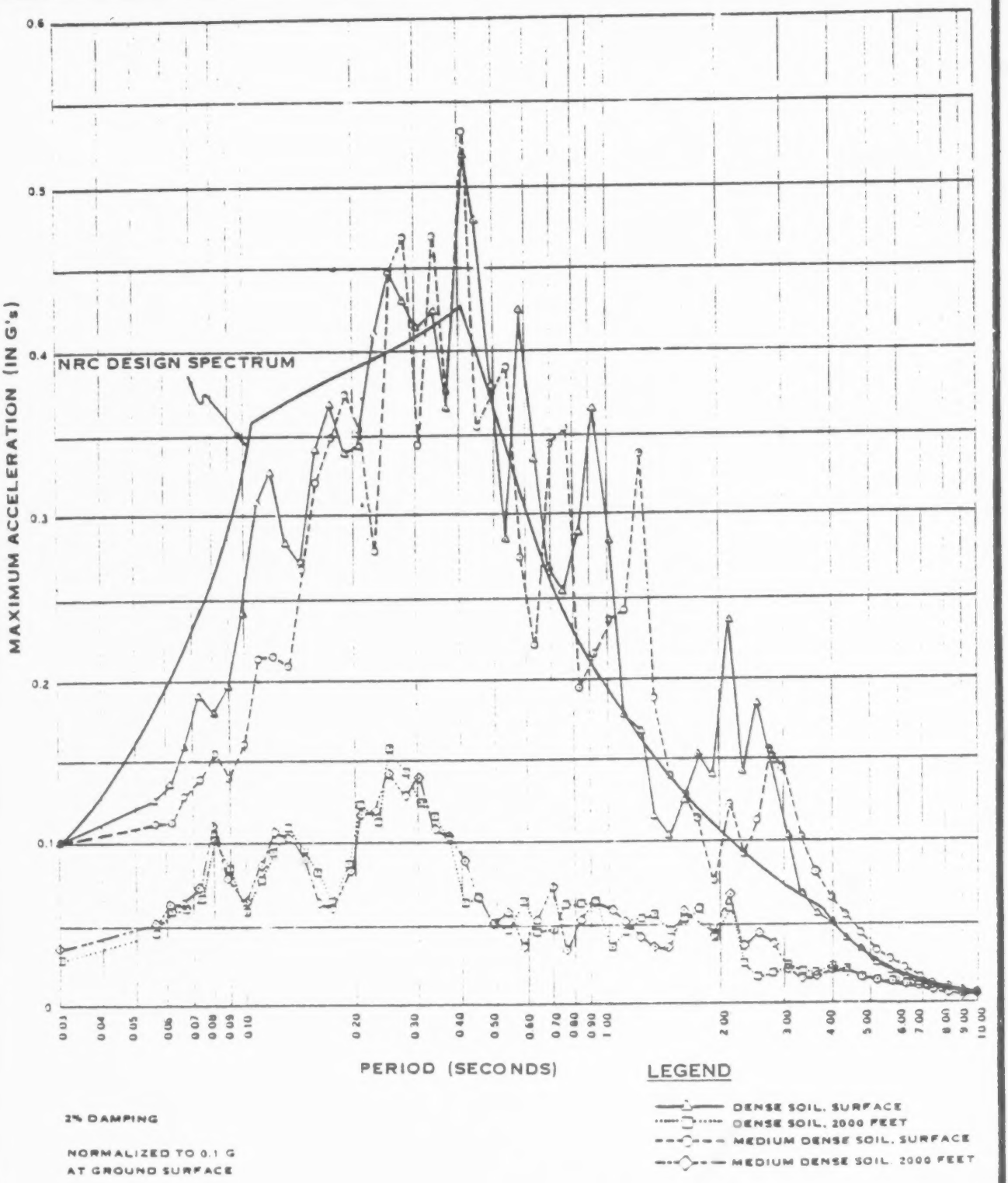

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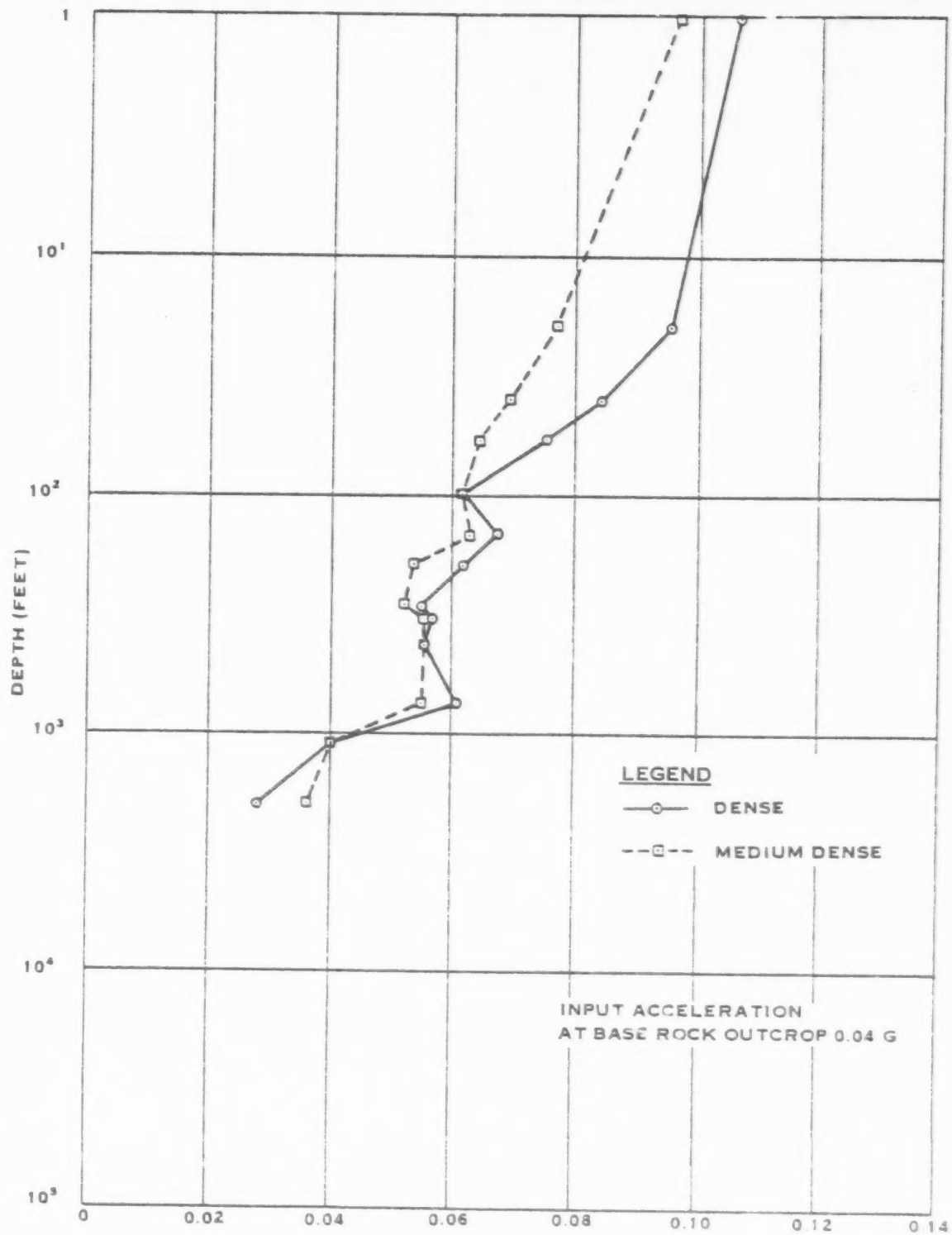
each soil condition is shown in Figure 2-23. The surface Regulatory Guide 1.60 response spectrum is also shown in Figure 2-22.

The NRC spectrum (Figure 2-22) significantly exceeds the calculated spectra for both the dense and medium-dense soil profiles in the high-frequency range. The surface structure design can be based on site-specific spectra such as those indicated by Figure 2-22 with attendant economy.

As evidenced in Figure 2-23, the acceleration amplification ratio between the exampled level at 610 meters (2,000 ft) and the surface has a value of approximately 3 for shear waves propagating vertically through the bedrock and surface unconsolidated soils.

The maximum design horizontal acceleration at the 610-meter (2,000-ft) depth in the salt dome, based on these analyses of vertically propogating shear waves, is 0.035g. This acceleration is compatible with a conservative 0.1g design surface acceleration.



PREPARED ___ DATE ___ REVISED ___ DATE ___ REVISED ___ DATE ___ APPROVED ___ DATE ___ T-1488-1	NATIONAL WASTE TERMINAL STORAGE PROGRAM GEOLOGIC EVALUATION GULF COAST SALT DOMES LAW ENGINEERING TESTING COMPANY MARIETTA GEORGIA	SEISMIC STABILITY ANALYSIS ACCELERATION AMPLIFICATION VS. DEPTH FOR DENSE AND MEDIUM DENSE MATERIALS JOB NO MV9600 FIGURE 2-23

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3 SELECTION OF SALT DOMES AND SURROUNDING STUDY AREAS

The Office of Nuclear Waste Isolation, Battelle Memorial Institute, has developed screening procedures to facilitate identification of potentially suitable National Waste Terminal Storage sites. The procedures provide for the following important milestones:

(1) Selection of a suitable geologic isolation medium (one medium selected was rock salt)

(2) Identification of study regions containing the selected medium type (the Gulf Interior Region encompasses a group of salt domes)

(3) Recommendation of several salt domes within the study areas (the subject of Area Characterization studies)

(4) Recommendation of preferred salt domes within the study areas for continuing studies

(5) Recommendation of preferred repository site(s) for further studies.

This chapter summarizes the screening procedure used to select study areas (the third milestone) within the Gulf Interior Region. The Gulf Interior Region encompasses portions of Texas, Louisiana and Mississippi. The screening procedure involved input from both the Geologic Project Manager, Law Engineering Testing Company, and the Regulatory Project Manager, Bechtel National Incorporated (BNI) (ONWI-18, 1979).

3.1 METHODOLOGY

The selection of salt domes within the Gulf Interior Region required a siting approach which was distinctly different from the screening procedures commonly used in widely distributed formations. In bedded salt formations, nongeologic screening specifications were used to identify areas of good siting potential. In this manner, areas which may have had conflicting uses were eliminated, and geologic studies were focused on those remaining areas of high potential. In the Gulf Interior Region, potential repository sites are fixed by salt dome locations. Consequently, it was necessary to ascertain which domes had attractive geologic properties and then define study areas to include the geologically attractive domes. The final consideration was to select those geologically attractive domes which minimize conflicts with nongeologic factors.

3.1.1 SCREENING HISTORY: Within the Gulf Coastal Province and adjacent offshore area in Texas, Louisiana, and Mississippi, there are more than 500 salt domes, with 263 known or suspected salt domes onshore. The onshore domes were evaluated by USGS. USGS concentrated on onshore salt domes because "siting in offshore salt structures would add unnecessary complications to a plan that requires assurance of a dry repository, including conventional shafts, conventional access, continuously reliable utilities, etc." Subsequent research-oriented studies were conducted by several organizations including, Netherland, Sewell & Associates (1975), Ledbetter, Kaiser and Ripperger (1975), Louisiana State

University Institute for Environmental Studies (Martinez and others, 1975), Mellen Geological Associates, Inc. (1976), and the Texas Bureau of Economic Geology (1980). In addition, USGS District Offices participated in the program. The results of these studies were used in the Gulf Interior Regional Characterization screening evaluation.

Evaluation criteria and screening specifications were developed to aid in preparation of plans for regional, area, and location and site studies (Brunton and McClain, 1977; Brunton and others, 1978; NUS Corporation, 1978). Plans for the Regional Characterization study were prepared for Texas (NUS Corporation, 1978), Mississippi (NUS Corporation, 1977a), and Louisiana (NUS Corporation, 1977b).

Geologic and hydrologic data characterizing the Gulf Interior Region were compiled by LETCo from available information and previous studies (Law Engineering Testing Company, 1978). Non-geologic data were compiled by BNI from available information (Bechtel National, 1978).

3.1.2 APPLICATION OF GEOLOGIC SCREENING SPECIFICATIONS: LETCo used the geologic screening specifications to identify domes that appeared to have high potential as National Waste Terminal Storage repositories. Three criteria dominated the screening:

(1) Dome tops should be at depths less than about 914 meters (3,000 ft).

(2) Domes should have areas greater than 405 hectares (1,000 acres) in lateral extent, plus a 152-meter (500-ft) buffer zone.

(3) Domes should not have been used by industry for petroleum or mineral production, storage, or other mineral-related use.

Eleven domes which exhibited the best geologic potential were identified.

3.1.3 APPLICATION OF NONGEOLOGIC SCREENING CRITERIA: BNI evaluated the 11 domes identified during the geologic screening, considering the likelihood of land-use conflicts and potential problems in licensing. These considerations relied upon nongeologic criteria (NUS Corporation, 1978) and nuclear licensing experience to avoid potential conflicts. A further objective was to select two or three domes in each basin to reduce study areas to manageable and economically feasible sizes.

3.2 SALT DOME AND SURROUNDING STUDY AREA IDENTIFICATION

The regional evaluation resulted in the recommendation of eight salt domes for additional studies during the Area Characterization phase of the program (Table 3-1). These domes were:

(1) Rayburn's Dome, LA
(2) Vacherie Dome, LA
(3) Cypress Creek Dome, MS
(4) Lampton Dome, MS
(5) Richton Dome, MS
(6) Keechi Dome, TX
(7) Oakwood Dome, TX
(8) Palestine Dome, TX.

Table 3-1. Results of Regional Characterization Screening

NORTHEAST AND SOUTH TEXAS BASINS

Dome	Recommended	Reason for Tentative Elimination
Bullard	no	Less than 1000 acres 500' barrier
PALESTINE	yes	-
Brooks	no	Lake
Grand Saline	no	Brine production
Steen	no	Less than 1000 acres +500' barrier
Butler	no	LPG storage, too small
Whitehouse	no	Less than 1000 acres +500' barrier
KEECHI	yes	-
Palangana	no	Brine and sulfur prod.
Mt. Sylvan	no	Urban and airport
Gyp Hill	no	Less than 1000 acres +500' barrier
East Tyler	no	LPG storage
OAKWOOD	yes	-
Hainesville	no	LPG storage
Piedras Pintas	no	Petroleum production
Bethel	no	Less than 1000 acres +500' barrier
Boggy Creek	no	Under major river
Day	no	More than 915 m deep
Brushy Creek	no	More than 915 m deep
Kittrell	no	More than 915 m deep
La Rue	no	More than 915 m deep
Concord	no	Less than 1000 acres +500' barrier & more than 915 m deep
Moca	no	More than 915 m deep
Dilworth Ranch	no	More than 915 m deep
Pescadito	no	More than 915 m deep

NORTH LOUISIANA BASIN

RAYBURNS	yes	-
Kings	no	Less than 1000 acres +500' barrier
Winnfield	no	Less than 1000 acres +500' barrier
Cedar Creek	no	Less than 1000 acres +500' barrier
VACHERIE	yes	-
Drakes	no	Less than 1000 acres +500' barrier
Gibsland	no	LPG storage
Protho	no	Petroleum production & too small
Prices	no	Less than 1000 acres +500' barrier
Arcadia	no	LPG storage
Minden	no	Petroleum production
Bistineau	no	Less than 1000 acres +500' barrier
Coochie Brake	no	Economic-held in reserve
Chestnut	no	Less than 1000 acres +500' barrier
Milam	no	Less than 1000 acres +500' barrier & more than 915 m deep
Chester	no	Less than 1000 acres +500' barrier & more than 915 m deep
Sikes	no	Less than 1000 acres +500' barrier & more than 915 m deep
Packton	no	Less than 1000 acres +500' barrier & more than 915 m deep
Castor Creek	no	Less than 1000 acres +500' barrier

MISSISSIPPI BASIN

McIntosh	no	Brine production
RICHTON	yes	-
Crowville	no	Less than 1000 acres +500' barrier
Tatum	no	Less than 1000 acres +500' barrier & nuclear test site
LAMPTON	yes	-
Petal	no	LPG storage
Gilbert	no	Less than 1000 acres +500' barrier
Hazelhurst	no	Less than 1000 acres +500' barrier
Arm	no	Less than 1000 acres +500' barrier
McLaurin	no	Less than 1000 acres +500' barrier
Richmond	no	Less than 1000 acres +500' barrier
Brumsburg	no	Less than 1000 acres +500' barrier
Byrd	no	Less than 1000 acres +500' barrier
Leedo	no	Less than 1000 acres +500' barrier
Raleigh	no	Less than 1000 acres +500' barrier

MISSISSIPPI BASIN (Continued)

Dome	Recommended	Reason for Tentative Elimination
McBride	no	Less than 1000 acres +500' barrier
County Line	no	Less than 1000 acres +500' barrier
Moselle	no	Less than 1000 acres +500' barrier
Sardis Church	no	Less than 1000 acres +500' barrier
Ikont	no	Less than 1000 acres +500' barrier & 66 Ivy Creek no less than 1000 acres +500' barrier
Centerville	no	Less than 1000 acres +500' barrier
D'Lo	no	Less than 1000 acres +500' barrier
Eminence	no	Less than 1000 acres +500' barrier
Midway	no	Less than 1000 acres +500' barrier
New Home	no	Less than 1000 acres +500' barrier
Oakley	no	Less than 1000 acres +500' barrier
Oakvale	no	Less than 1000 acres +500' barrier
Ruth	no	Less than 1000 acres +500' barrier
Walnut Bayou	no	Less than 1000 acres +500' barrier
Monticello	no	Less than 1000 acres +500' barrier
Allen	no	Less than 1000 acres +500' barrier
Prentiss	no	Less than 1000 acres +500' barrier
Carmichael	no	Less than 1000 acres +500' barrier & more than 915 m deep
Bothwell	no	Less than 1000 acres +500' barrier & more than 915 m deep
South Tallulah	no	More than 915 m deep
Edwards	no	More than 915 m deep
Caseyville	no	More than 915 m deep
Kola	no	More than 915 m deep
Carson	no	More than 915 m deep
Utica	no	More than 915 m deep
Coleman	no	More than 915 m deep
Hervey	no	More than 915 m deep
Wesson	no	More than 915 m deep
Kings	no	More than 915 m deep
Halifax	no	More than 915 m deep
Glass	no	More than 915 m deep
Ashwood (Somerset)	no	More than 915 m deep
Newellton	no	More than 915 m deep
Singer	no	More than 915 m deep
Vicksburg	no	More than 915 m deep
Eagle Bend	no	More than 915 m deep
Galloway	no	More than 915 m deep
Learned	no	More than 915 m deep
North Tallulah	no	More than 915 m deep
Brownsville	no	More than 915 m deep
Oakridge	no	More than 915 m deep
Newman	no	More than 915 m deep
Duck Port	no	More than 915 m deep
Sunrise	no	More than 915 m deep
Snake Bayou	no	More than 915 m deep
Foules	no	More than 915 m deep
Glazier	no	More than 915 m deep
Heidleberg	no	More than 915 m deep
Gwinville	no	More than 915 m deep
South Carolton	no	More than 915 m deep
Burns	no	More than 915 m deep
Yellow Creek	no	More than 915 m deep
Eucutta	no	More than 915 m deep
Laurel	no	More than 915 m deep
Valley Park	no	More than 915 m deep
Rufus	no	More than 915 m deep
Ovette	no	More than 915 m deep
Hiwanee	no	More than 915 m deep
Easterville	no	More than 915 m deep
Ellisville	no	More than 915 m deep
Grange	no	More than 915 m deep
CYPRESS CREEK (New Augusta)	yes	-
Hubbard	no	Less than 1000 acres +500' barrier & more than 915 m deep
Zion Hill Church	no	Less than 1000 acres +500' barrier

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In accordance with the previously published plans (NUS Corporation, 1978), an area of about 2,590 to 5,180 km^2 (1,000 to 2,000 mi^2), which encompassed the recommended domes, was identified in each basin (see Figures 1-2, 1-3, and 1-4).

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4 AREA CHARACTERIZATION SUMMARY

The purpose of this chapter is to summarize the geologic and hydrologic information contained in the Geologic Area Characterization reports for Gulf Coast salt dome studies prepared by Law Engineering Testing Company (1980). The data presented for summary have been extracted from the Area Characterization reports: East Texas Study Area, North Louisiana Study Area, and Mississippi Study Area.

The scope of this chapter includes a summary of the geologic and hydrologic characteristics of the North Louisiana, Mississippi, and East Texas Study Areas and the candidate domes that were studied in these areas (Figure 4-1). The candidate domes include Rayburn's and Vacherie Domes in north Louisiana, Cypress Creek, Lampton, and Richton Domes in Mississippi, and Keechi and Oakwood Domes in east Texas. Palestine Dome in Texas, initially a candidate dome, was eliminated from consideration early in the study because of collapse features caused by dissolution of the salt stock associated with past brining operations.

Area Characterization studies addressed the National Waste Terminal Storage (NWTS) Geologic Site Qualification Criteria (Table 4-1). The NWTS Geologic Site Qualification Criteria consist of site geometry, geohydrology, geochemistry, geologic characteristics, tectonic environment, human resources, and surface characteristics.

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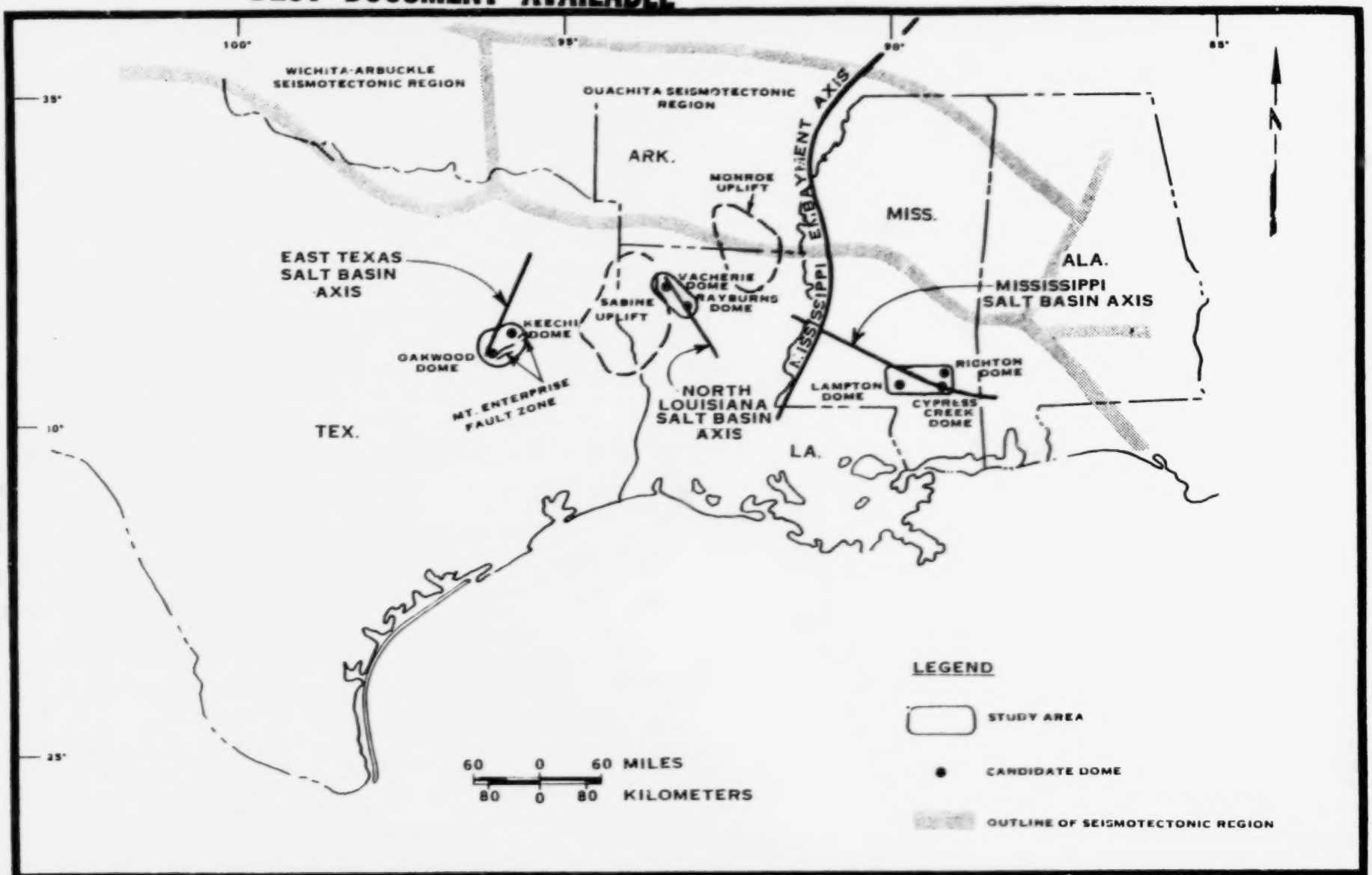

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NATIONAL WASTE TERMINAL STORAGE PROGRAM
GEOLOGIC EVALUATION GULF COAST SALT DOMES
LAW ENGINEERING TESTING COMPANY
MARIETTA, GEORGIA

LOCATION MAP OF STUDY AREAS AND CANDIDATE DOMES

JOB NO. MV9600 FIGURE 4-1

FIGURE 4-1

TABLE 4-1.

NWTS SITE QUALIFICATION CRITERIA

(from DOE/NWTS - 33(2), 1981)

Criterion Number	Criterion
I.	Site Geometry . Minimum Depth . Thickness . Lateral Extent
II.	Geohydrology . Geohydrological Regime/Aquifer Characterization . Hydrological Regime/Modeling/Surface-Subsurface . Geohydrological Regime/Shaft Seals/Flow Rates . Subsurface Dissolution Rates
III.	Geochemistry . Geochemical Interaction . Radionuclide Retardation
IV.	Geologic Characteristics . Stratigraphy Characterization . Host Rock/Stress Phenomena . Rock Strength/Development, Operation, and Closure
V.	Tectonic Environment . Tectonic Element Evaluation . Quaternary Faults . Quaternary Igneous Activity . Uplift/Subsidence . Seismicity/Ground Motion/Credible Earthquake
VI.	Human Resources . Resources . Exploration History/Use . Land Ownership/Access
VII.	Surface Characteristics . Surficial Hydrological System/Characteristics

It was not necessary to investigate all criteria to the same extent during these studies. The geologic criteria, including site geometry, geologic characteristics, tectonic environment and human resources, were investigated in detail during the Area Characterization phase in order to provide a framework for later studies. Other criteria and subcriteria, such as modeling of the geohydrologic regime, shaft construction feasibility in terms of the geohydrologic regime, radionuclide retardation and host rock/stress phenomena, and strength, will be thoroughly addressed during Site Characterization.

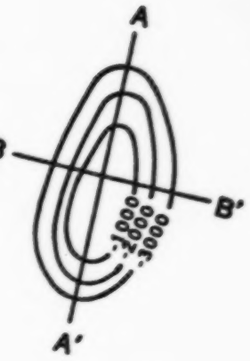
4.1 SITE GEOMETRY

Domal models were prepared by computer modeling using gravity data, high-resolution seismic reflection data (where available), and well data (Figure 4-2). These models were used to investigate the minimum depth to caprock and salt, and the thickness and lateral extent of the salt stock.

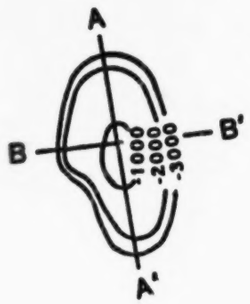
4.1.1 MINIMUM DEPTH: Extreme sea level changes may result in inundation and erosion over the candidate domes. Maximum sea level changes would occur either as a result of the complete melting of existing ice sheets and glaciers (rise of sea level) or the return of the maximum extent of continental glaciation (lowering of sea level). The ground-surface elevation over the dome; the minimum depth to, and the maximum elevation of, the top of the caprock and salt encountered in wells; and the estimated effects of maximum sea level changes during the next 250,000 years are presented in Table 4-2.

CYPRESS CREEK

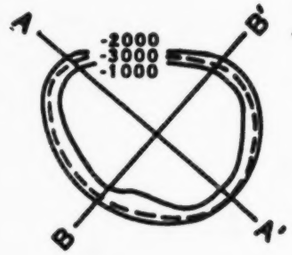
KEECHI



LAMPTON

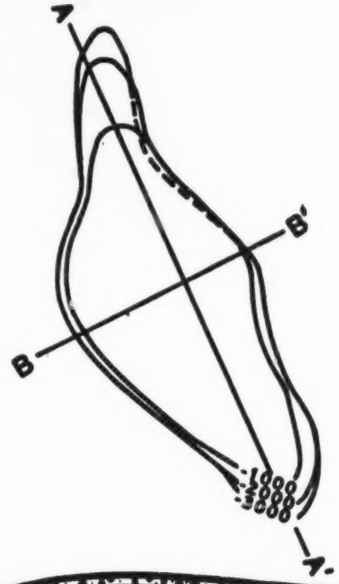


OAKWOOD

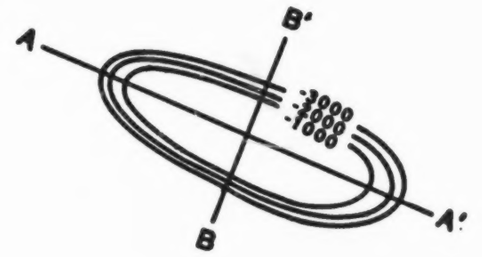


RAYBURNS

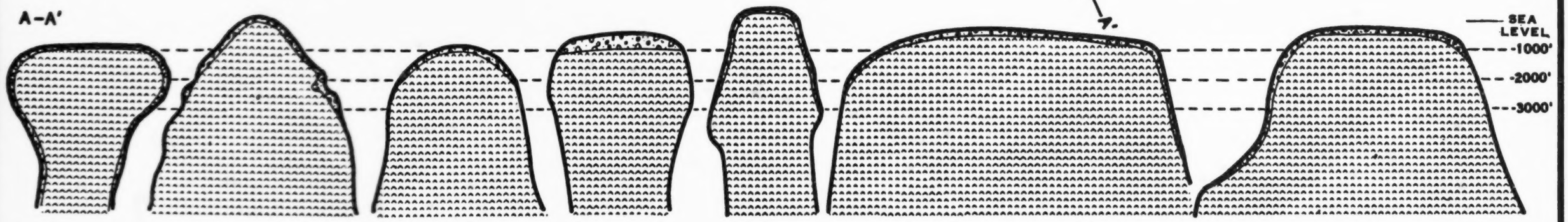
RICHTON



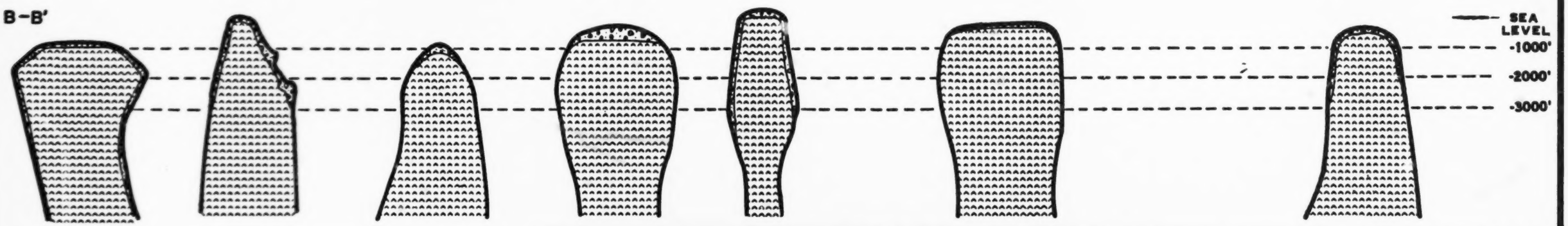
VACHERIE



A–A'



B–B'



VERTICAL EXAGGERATION X 3

0 5,000 10,000
SCALE IN FEET

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NATIONAL WASTE TERMINAL STORAGE PROGRAM
GEOLOGIC EVALUATION GULF COAST SALT DOMES
LAW ENGINEERING TESTING COMPANY
MARIETTA, GEORGIA

SALT CONTOURS AND CROSS SECTIONS OF THE SEVEN CANDIDATE DOMES

JOB NO. MV9600 FIGURE 4-2

BEST DOCUMENT AVAILABLE

TABLE 4-2.
ESTIMATED EFFECTS OF MAXIMUM SEA LEVEL CHANGES

Dome	Ground Surface Elevation[1] (ft)[4]	Minimum Depth and Maximum Elevation for Top of Caprock[2] (ft/ft)	Minimum Depth and Maximum Elevation for Top of Salt[2] (ft/ft)	Minimum Depth to Salt After Lowering of Sea Level 525 Feet (ft)	Possible Inundation From 270-Foot Sea Level Rise	Possible Inundation From 360-Foot Sea Level Rise
Oakwood	300 to 550	713/-357	1016/-604	454	None	Partial
Keechi	320 to 500	125/225	435/-85	None, Breached	None	Partial
Vacherie	165 to 395	543/-299	799/-558	492	Partial	Total
Rayburns	120 to 320	18/174	115/94	None, Breached	Partial	Total
Richton	165 to 290	497/-264	722/-508	138	Partial	Total
Lampton	190 to 370	1305/-1000	1646/-1360	1000	Partial	Partial
Cypress Creek	180 to 270	1172/-951	1271/-1037[3]	657	Total	Total

1 Data are mean sea level.
2 Minimum depth and maximum elevation are not coincident in space.
3 Uncorrected for directional drilling.
4 To convert to meters, multiply by 0.3048.

Estimates of the maximum increase of sea level to be expected during the next 250,000 years ranged between 82 and 110 meters (270 and 360 ft). Andrews (1975) assumed that the present shorelines are vertical walls rather than slopes and estimated a sea level rise of 110 meters (360 ft) from a complete melting. Lamb (1971), using more soundly based assumptions, calculated a rise of 82 meters (270 ft). Cypress Creek, Vacherie, Rayburn's, and Richton Domes would be totally inundated by a 110-meter (360-ft) rise.

Estimates of the maximum lowering of sea level during continental glaciation ranged from 100 to 160 meters (330 to 525 ft) (Andrews, 1975; Donn and others, 1962). Although sub-sea data for a 160-meter (525-ft) lowering is lacking, this extreme value is used in Table 4-2 to provide a conservative depth to salt at each dome after regraded stream erosion. On the basis of these calculations, maximum sea-level lowering during glaciation may result in exposure of the salt at Rayburn's and Keechi Domes.

Seafloor erosion during a sea level rise could expose caprock at Rayburn's Dome.

4.1.2 VERTICAL THICKNESS OF SALT: The vertical thickness of salt at each dome from the top of the dome to an elevation of -914 meters (-3,000 ft) MSL varies between 500 and 967 meters (1,640 and 3,174 ft) (Table 4-3). Rayburn's Dome has the greatest vertical thickness of salt, and Lampton Dome the least.

TABLE 4-3.
VERTICAL THICKNESS OF SALT

Dome	Maximum Elevation* of Top of Salt (ft)	Vertical Thickness of Salt Above Elevation -3000 Feet (ft)**
Oakwood	-604	2396
Keechi	-85	2915
Vacherie	-558	2442
Rayburns	174	3174
Richton	-508	2492
Lampton	-1360	1640
Cypress Creek	-1037***	1963

*Data are mean sea level
**To convert to meters, multiply by 0.3048.
***Uncorrected for directional drilling.

4.1.3 LATERAL EXTENT OF SALT: The total horizontal area for each dome was measured at elevations of -610, -762, and -914 meters (-2,000, -2,500, and -3,000 ft) MSL (Table 4-4). Of the seven domes studied, Rayburn's Dome has the smallest area, and Richton Dome the largest.

4.2 GEOHYDROLOGY

Area and near-dome geohydrologic studies were conducted during Area Characterization. Ground-water reservoir characteristics, ground-water movement, and ground-water reservoir uses were investigated in each of the study areas. One-dimensional models

TABLE 4.4.
TOTAL AREA OF DOMES AT
SELECTED ELEVATIONS

Dome	Total Area (acres) at Selected Elevations		
	Elevation* (ft)**		
	-2000	-2500	-3000
Oakwood	2785	2694	2613
Keechi	1180	1385	2070
Vacherie	2031	2379	2730
Rayburns	790	924	1082
Richton	5585	5825	5847
Lampton	1075	1148	1236
Cypress Creek	3217	2906	2609

*Data are mean sea level
**To convert to meters, multiply by 0.3048.

for estimating ground-water flow times along assumed upward vertical flow paths near the domes were developed. Domal area geohydrology and the water-transmitting properties of domal caprock were investigated, and saline anomalies in the vicinity of candidate domes were identified.

4.2.1 GENERAL GEOHYDROLOGIC SETTING: The regional stratigraphy and water bearing characteristics of the sediments were characterized in the Mississippi, North Louisiana, and East Texas study areas (Table 4-5).

TABLE 4-5.

GENERALIZED STRATIGRAPHY & WATER BEARING CHARACTERISTICS OF GEOLOGIC UNITS

A. MISSISSIPPI STUDY AREA

SYSTEM	SERIES	GEOLOGIC UNIT	DOMINANT LITHOLOGY	WATER BEARING CHARACTERISTICS
QUATERNARY	Plio-Pleistocene to Plio-Miocene	Citronelle Formation	Unconsolidated sand and gravel, fine- to coarse-grained quartzose sand with traces of chert and some clay.	Transmits small quantities of water. Yields of wells tapping this aquifer are generally small. A few wells can produce up to 200 gpm but most are domestic wells, although a few wells produce enough for municipal needs. Chemically, water is low in dissolved solids. and pH.
TERTIARY	Miocene	Hattiesburg Formation Undifferentiated	Interbedded sand and clay. Sand is fine-grained at the top and grades to coarse-grained granular quartz. Pyrite is common throughout.	A highly transmissive water-bearing formation. An important source of water supply for municipal, industrial, and domestic wells in southern Mississippi. Pumping rates very from 125 to 850 gpm. Chemically, water is low in total dissolved-solids.
		Catahoula Formation Undifferentiated		
	Oligocene	Chickasawhay Formation Undifferentiated		
		Vicksburg Group	Predominantly sandy limestone, clay, marl, and fossiliferous sandstone.	Not an important aquifer. Supplies some domestic wells in the northern part of the salt basin. Contains slightly saline water in the southern parts of the basin.
	Eocene	Jackson Group	Calcareous clay and fossiliferous and glauconitic sandy limestone.	Not an aquifer in this area. Sand member in upper part is considered minor local aquifer in northeastern part of salt-dome basin.
		CLAIBORNE GROUP: Cocofield Formation	Consists of beds of fine- to medium-grained sand; sandy carbonaceous clay, and thin beds of lignite. Beds of interbedded clay and limestone occur locally.	High transmissivities and hydraulic conductivities north of study area, with yields decreasing downdip in the study area. Because of high dissolved solids and excessively colored water, aquifer utilization is limited in the study area.
		CLAIBORNE GROUP: Cook Mountain Formation	Limestone, variable, crystalline to fossiliferous, contains some sand and silt.	Generally not considered an aquifer, but can transmit water locally. Utilization is limited in the study area due to high salinity. This formation is used for brine disposal in southern Mississippi. Aquifer tests conducted by LETCo show very low transmissivities.
		CLAIBORNE GROUP: Kosciusko (Sparta) Formation	Limestone, clay, and sand interbedded. Updip of study area formation is composed predominantly of rounded quartz grains.	Good fluid transmitting properties updip of study area where Sparta is extensively utilized for public and industrial water supplies. Due to high salinity and depth of the formation, utilization is limited in the study area. Transmissivities computed from LETCo aquifer tests show that the Sparta is capable of transmitting fluids.
		CLAIBORNE GROUP: Tallahatta, Winona, and Tallahatta Formations	Alternating beds of clay and limestone with some beds of siltstone and shale. Limestone is variable generally glauconitic and fossiliferous.	Does not transmit water readily.
		Wilcox Group	Interbedded sand, clay, and siltstone, with minor shale, limestone, and lignite. Sand is very fine- to fine-grained.	Capable of transmitting water north of the study area. Transmissivity and hydraulic conductivity of this formation is reduced in the study area due to the fine-grained character of the sands. Water produced from this formation in the study area is highly saline and may contain gas.
	Paleocene	Midway Group	Predominantly clay, with interbedded sand, shale, and lignite. Lignite, pyrite, and glauconite are common throughout.	Does not transmit water readily.

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TABLE 4-5.

GENERALIZED STRATIGRAPHY & WATER BEARING CHARACTERISTICS OF GEOLOGIC UNITS (CONTINUED)

B. LOUISIANA STUDY AREA

SYSTEM	SERIES	GEOLOGIC UNIT		DOMINANT LITHOLOGY	WATER TRANSMITTING CHARACTERISTICS
QUATERNARY	Recent	Alluvium		Gravels, sands, silts and clays.	Yields small to large quantities of water to wells regionally. Uses vary from domestic supply to irrigation supply. Hydraulic conductivity ranges from 100 feet/day to 300 feet/day (Hosman, 1978).
	Pleistocene	Terrace Deposits		Fluvial sequences of gravel, sand, silt and clay.	
TERTIARY	Eocene	CLAIBORNE GROUP	Cockfield Formation	Massive to cross-bedded, glauconitic quartz sands with interbedded silts and clays, fossils and plant material.	These formations are capable of transmitting small quantities of water locally. The hydraulic conductivity of the Cockfield Formation ranges from less than 15 feet/day to more than 40 feet/day (Hosman, 1978). These formations are present in only a small portion of the study area. Generally the Cook Mountain is not water bearing.
			Cook Mountain Formation	Fossiliferous, glauconitic, clay ironstone interbedded with brown clay and silty sands.	
			Sparta Formation	Massive, fine-grained, cross-bedded sands interbedded with sandy clays. Contains occasional lignites and fossils.	This formation is capable of transmitting large quantities of water. It is the principal aquifer in northern Louisiana. Hydraulic conductivities of this formation in the study area as determined by LETCo from aquifer tests, ranged from 1.6 feet/day to more than 100 feet/day.
			Cane River Formation	Interbedded silt and clay basal unit and upper unit. Middle of this formation is a glauconitic fossiliferous marl.	This formation is generally considered to have poor water transmitting properties regionally.
			Carrizo Formation	Fine- to coarse-grained, massive sands with minor amounts of clays, silts and lignites.	The Carrizo Formation is capable of transmitting water regionally. One LETCo aquifer test in this formation resulted in an average hydraulic conductivity value of 7.0 feet/day.
	Paleocene	Wilcox Group		Deltaic sequence of sands, silts, clays and lignites with interbeds of marine sands and clays.	Deposits of the Wilcox Group are capable of transmitting water regionally. Hydraulic conductivities of these deposits in the study area as determined from LETCo aquifer tests, ranged from 0.11 feet/day to 7.7 feet/day.
		Midway Group		Micaceous, fossiliferous, lignitic carbonaceous shale grading upward into sand.	These deposits are generally considered to have poor water transmitting properties regionally.
UPPER CRETACEOUS	Gulfian	NAVARRO GROUP	Arkadelphia Formation	Predominantly chalky marl with interbedded shales and clays.	This formation is generally considered to have poor water transmitting properties regionally.
			Nacatoch Formation	Marls and chalks grading upwards into fine grained sand.	This formation has good water transmitting properties in its outcrop area in southern Arkansas. In the study area, this formation generally has poor water transmitting properties. Results of aquifer testing by LETCo in the study area gave a hydraulic conductivity range of 0.03 to 1.0 feet/day.
			Saratoga Formation	Fossiliferous chalk with thin shale beds.	This formation is generally considered to have poor water transmitting properties regionally.
		Taylor Group		Predominantly chalk, shale, and marl all interbedded.	This formation is generally considered to have poor water transmitting properties regionally.
		AUSTIN GROUP	Brownstown Formation	Fine- to medium-grained sand with shale interbeds.	The Tokio Formation has good water transmitting properties in its outcrop area in southern Arkansas. In the study area, undifferentiated deposits of the Austin Group have fair water transmitting properties. Results of aquifer testing by LETCo in the study area gave a hydraulic conductivity value of 1.4 feet/day.
			Tokio Formation	Calcareous sands and shale, with some chert gravels, basal marls and chalk.	
		Eagle Ford Group		Micaceous silty shale with thin lenses of fine-grained sandstones and limestones.	This formation is generally considered to have poor water transmitting properties regionally.
		Tuscaloosa Group		Interbedded sand and shale with some calcareous beds; and a massive basal glauconitic sandstone.	This Group is capable of transmitting small quantities of water in its outcrop area in southern Arkansas.

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TABLE 4-5.

GENERALIZED STRATIGRAPHY & WATER BEARING CHARACTERISTICS OF GEOLOGIC UNITS (CONTINUED)

C. TEXAS STUDY AREA

SYSTEM	SERIES	GEOLOGIC UNIT		DOMINANT LITHOLOGY	WATER BEARING CHARACTERISTICS
Quaternary	Recent & Pleistocene	Terrace & Alluvium		Unconsolidated sand, silt, clay & some gravel	Aquifer not present everywhere in study area. Generally transmits small amounts of water to wells. Quality of water fair, but wells are easily contaminated by improper disposal practices.
Tertiary	Eocene	CLAIBORNE GROUP	Cook Mountain Formation	Glauconitic sand interbedded with silt and clay	Yields water in small amounts to domestic wells. Limited to 30-50 gpm in the study area. Water quality is variable with high total dissolved solids.
			Sparta Formation	Fine to medium-grained sand with glauconitic clay and silt	Transmissivity of this formation is moderate to high. It is a source of water supply to many communities in the study area. Water quality is good with low TDS. Some wells have high iron content.
			Weches Formation	Glauconitic sand and shale	Does not transmit water readily. It is not considered an aquifer.
			Queen City Formation	Medium to fine-grained sand interbedded with silt and clay	Transmissivity of this formation is low and yields of wells tapping this aquifer are generally less than 250 gpm. Water produced from this aquifer is of good chemical character, but can contain high nitrates in shallow wells.
			Reklaw Formation	Upper part is silty with carbonaceous clay, lower part is silty with some sand	Yields only small amounts of water in its outcrop. In the subsurface this formation does not readily transmit water to wells.
			Carrizo Formation	Upper portion is silty sand and clay. Lower portion is massive medium to fine sand	Yields large amounts of water to wells in the study area and is an abundant supply source. Water quality is good and water produced is soft and acceptable for a variety of uses.
			Wilcox Group	Interbedded fine-grained sand, silt and shale	Transmissivity is variable, generally less than that of the overlying Carrizo, but not as low as the Queen City. Lenticular nature of this group makes water supply development possible only locally. Water quality is similar to the overlying Carrizo Formation.
	Paleocene		Midway Group	Micaceous, calcareous shale with some thin beds of fine-grained sand.	Does not transmit water readily. It is not considered an aquifer.
Cretaceous	Upper Cretaceous	NAVARRO GROUP	Upper Navarro	Silty shale interbedded with marl and siltstone	Does not transmit water readily. It is not considered an aquifer.
			Nacatoch Formation	Fine-grained sand, sandy clay, calcareous sandy marl	Yields small to moderate amounts of water in its outcrop only in the north central part of the study area. Water quality is variable.
			Lower Navarro	Limestone, marl, and clay	Does not transmit water readily. It is not considered an aquifer.
			Taylor Group	Clay, marl and chalk with some sandy marl	These units do not trasmit water readily in the study area. They are not considered to be aquifers.
			Austin Group	Chalk, marl and limestone	
			Eagle Ford Group	Shale with thin laminated beds of sandstone and limestone	
			Woodbine Group	Fine to medium-grained calcareous and non-calcareous sands and sandstones. Interbedded with shales	Information on this group's water-bearing characteristics in the study area is not available. Units in this group may be capable of transmitting small quantities of saline water to wells.

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In Mississippi, strata of regional hydrologic interest were those of Tertiary and Quaternary ages. Tertiary sediments are predominantly interbedded clays and sands which dip southwestward at a rate of 2 to 9 m/km (10 to 45 ft/mi) and thicken to the southwest. Quaternary deposits, which overlie Tertiary deposits, occur as alluvium in stream valleys and terrace deposits.

Strata of regional hydrologic concern that occur in the North Louisiana Study Area are those of Upper Cretaceous, Tertiary and Quaternary ages. The Cretaceous sediments consist of sandstones, shales, marls, chalks, and some limestones. The Tertiary sediments consist of a thick sequence of alternating marine clays and sands of Paleocene and Eocene age. Regionally, Upper Cretaceous and Tertiary sediments generally dip and thicken to the southeast. The rate of dip is approximately 19 m/km (100 ft/mi).

Regionally, in the East Texas Study Area, strata of principal hydrologic concern are those of Upper Cretaceous and Tertiary ages. Upper Cretaceous sediments consist of interbedded sandstones, shales, and calcareous deposits of deltaic or shallow marine origin that dip east-southeasterly (gulfward) from 4 to 19 m/km (20 to 100 ft/mi). Tertiary sediments consist primarily of interbedded sands, shales, and clays, and are overlain by Quaternary deposits. These deposits occur in stream valleys as terrace remnants.

Piercement salt domes locally affect the dip, strike, and thickness of the geologic strata they penetrate, as well as the overlying beds, in all three study areas. The structural complexities around and over a salt dome may also influence its

hydrologic relationship with the surrounding and overlying strata.

4.2.1.1 Hydrogeologic Characterization of the Study Areas:

In the Mississippi Study Area the ground-water reservoir includes aquifers of the Wilcox Group, as well as the stratigraphically higher Miocene and younger deposits which include the Chickasawhay, Catahoula, Hattiesburg, and Citronelle Formations. The Midway Group is assumed to be the base of the ground-water reservoir because it contains thick impermeable beds that hinder the flow of water between overlying and underlying formations. The water table that occurs in the Quaternary and Miocene deposits is considered the upper limit of the ground-water reservoir.

In the North Louisiana Study Area the ground-water reservoir includes aquifers of the Tuscaloosa Group, Austin Group, Nacatoch Formation, Wilcox Group, Carrizo Formation, Sparta Formation, and Cockfield Formation. The base of the ground-water reservoir has not been defined, but probably occurs in the Lower Cretaceous sediments. The water table in the Quaternary and Tertiary deposits is considered to be the upper limit of the ground-water reservoir. Cretaceous deposits that crop out north of the study area in southern Arkansas and eastern Texas are exposed locally around some salt domes within the study area.

Within the East Texas Study Area, beds of Upper Cretaceous and Tertiary ages that are considered to be regional aquifers include the Woodbine Group, Wilcox Group and the Carrizo, Queen City, and Sparta Formations of the Claiborne Group. The Wilcox-

Carrizo aquifer system is the largest supply of fresh ground water in the study area. The base of the ground-water reservoir has not been defined, but probably occurs in the Lower Cretaceous sediments. The water table in the Quaternary deposits is considered the upper limit of this reservoir.

4.2.1.1.1 Water Transmitting Properties of Geologic Formations- The hydraulic properties of aquifers underlying the three study areas were determined from aquifer tests, geophysical logs, and laboratory analysis of side-wall cores. In Mississippi, the Wilcox Group and the Hattiesburg, Catahoula, and Citronelle Formations are considered to have good water-transmitting properties; formations of the Claiborne Group generally have poor water-transmitting properties. In Louisiana, the Wilcox Group and the Sparta and Carrizo Formations were found to generally have good water-transmitting properties; the Nacatoch Formation and Austin Group generally were found to have poor water-transmitting properties. Geologic units found to have good water-transmitting properties in Texas are the combined Wilcox-Carrizo Units and the Sparta Formation. Geologic units with poor water-transmitting properties are the Navarro and Midway Groups and the Reklaw, Weches, and Cook Mountain Formations of the Claiborne Group. Aquifer test results for the three study areas are summarized in Table 4-6.

The high degree of variation in permeability of the aquifer systems indicates that although formations may be classified

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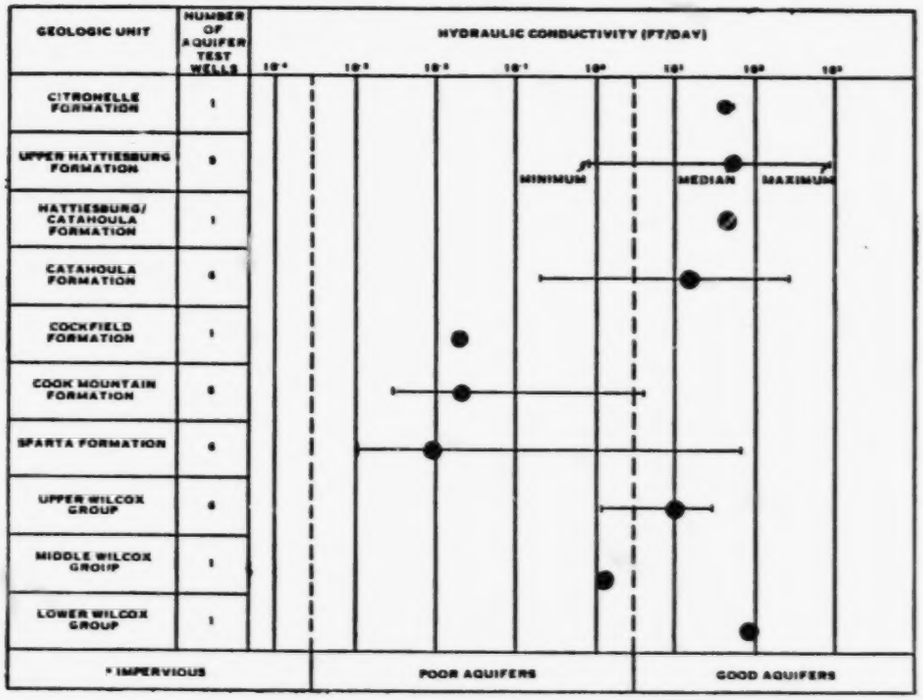
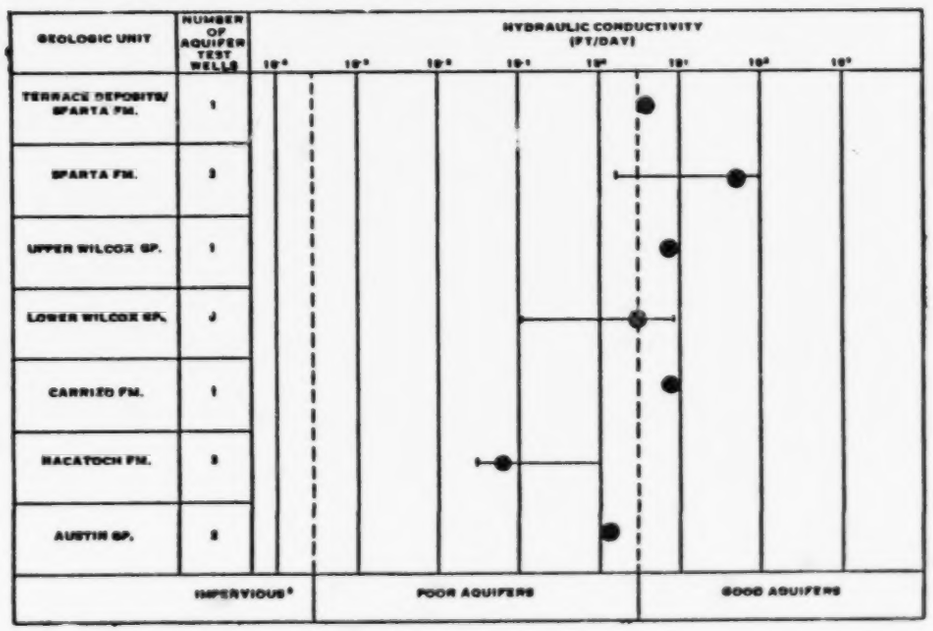
MISSISSIPPI STUDY AREA



NORTH LOUISIANA STUDY AREA



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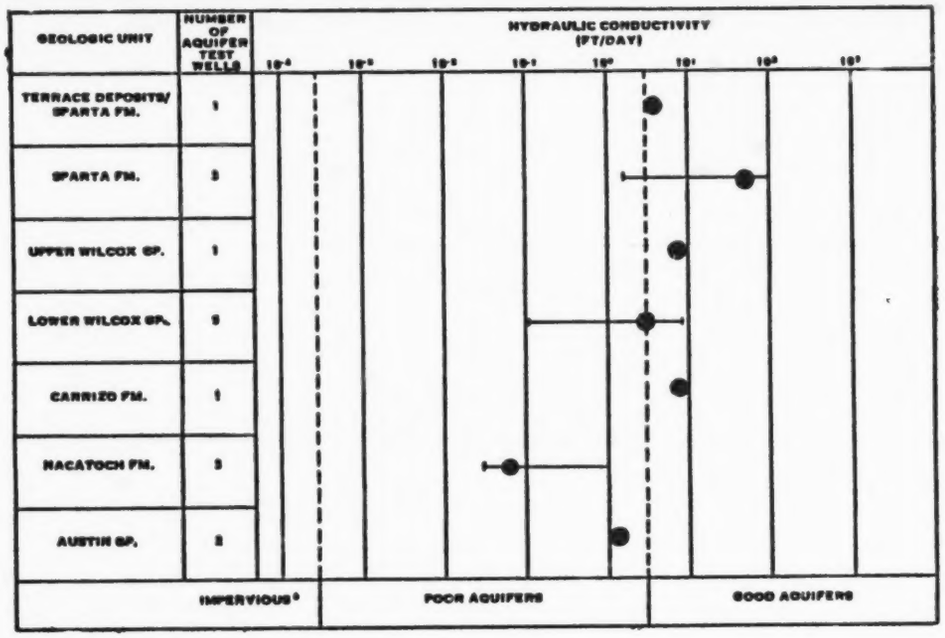
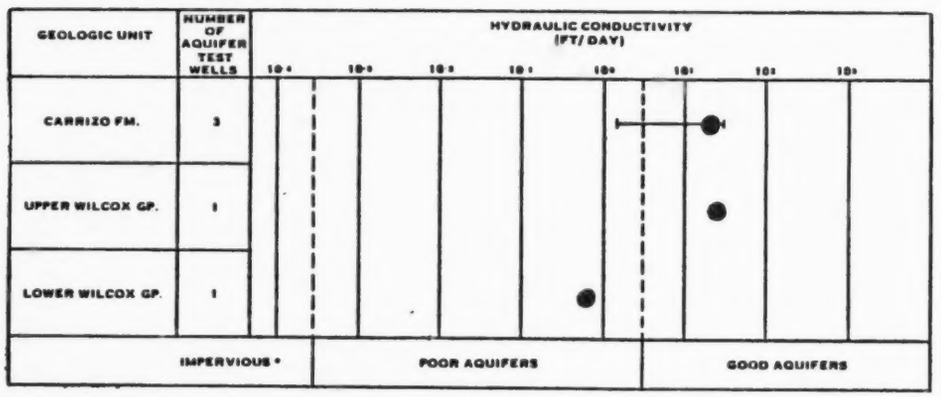


EAST TEXAS STUDY AREA



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* MODIFIED FROM FAIR AND GEYER, 1958.

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REVISED	DP	DATE	11/20/81
REVISED		DATE	
APPROVED	RJM	DATE	11/30/81

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NATIONAL WASTE TERMINAL STORAGE PROGRAM
GEOLOGIC EVALUATION GULF COAST SALT DOMES

LAW ENGINEERING TESTING COMPANY
MARIETTA GEORGIA

AQUIFER TEST SUMMARY FOR SEDIMENTS

JOB NO. MV9600

TABLE 4-6

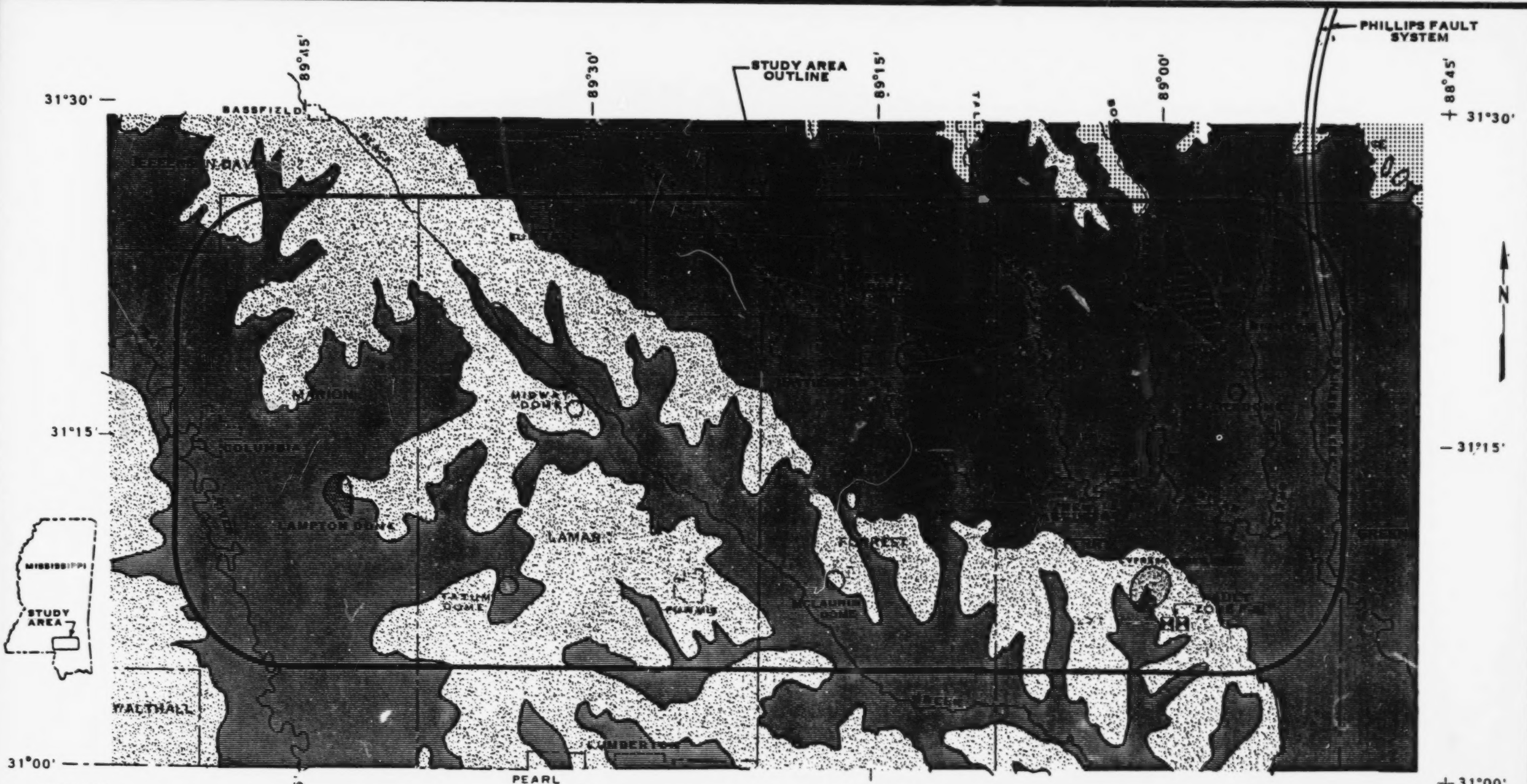
regionally as either good or poor aquifers, locally they may fall into either category.

4.2.1.1.2 Fresh Ground-Water Occurrence - Areas of fresh ground-water recharge and discharge were identified, both regionally and near the domes.

In general, recharge to deposits of Tertiary age in Mississippi occurs north of the study area in areas where these deposits are exposed at the surface and can be replenished by rainfall.

The Citronelle Formation and undifferentiated Hattiesburg and Pascagoula Formations are exposed in the study area (Figure 4-3). Ground-water recharge to these formations is directly from precipitation, and hydraulic connection between these formations and streams is common. Discharge occurs to major streams from the near-surface deposits in the vicinity of Richton and Cypress Creek domes.

Ground-water recharge in Louisiana occurs in the Quaternary and Tertiary deposits which are exposed in the study area (Figure 4-4) and Cretaceous deposits that crop out north of the study area. Recharge to these deposits is derived principally from rainfall and streams in the outcrop areas. Additional recharge may occur as interaquifer leakage downdip from the outcrop. Fresh ground water is discharged into major streams from near-surface deposits. This discharge is greatest in the southern and eastern portions of the study area and least in the northwest



LEGEND

- PLIO-PLEISTOCENE — CITRONELLE FORMATION
- MIOCENE — PASCAGOULA-HATTIESBURG FORMATION
- MIOCENE — CATAHOULA FORMATION
- AREA OF CANDIDATE SALT DOME AT -3000 FEET MSL.
- NON-CANDIDATE SALT DOME

GEOLOGY FROM MISSISSIPPI GEOLOGICAL SURVEY GEOLOGIC MAP OF MISSISSIPPI (1968)

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REVISED		DATE
APPROVED	RSM	DATE 9/28/81

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NATIONAL WASTE TERMINAL STORAGE PROGRAM
GEOLOGIC EVALUATION GULF COAST SALT DOMES
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GEOLOGIC MAP FOR MISSISSIPPI STUDY AREA

JOB NO. MV9600

FIGURE 4-3

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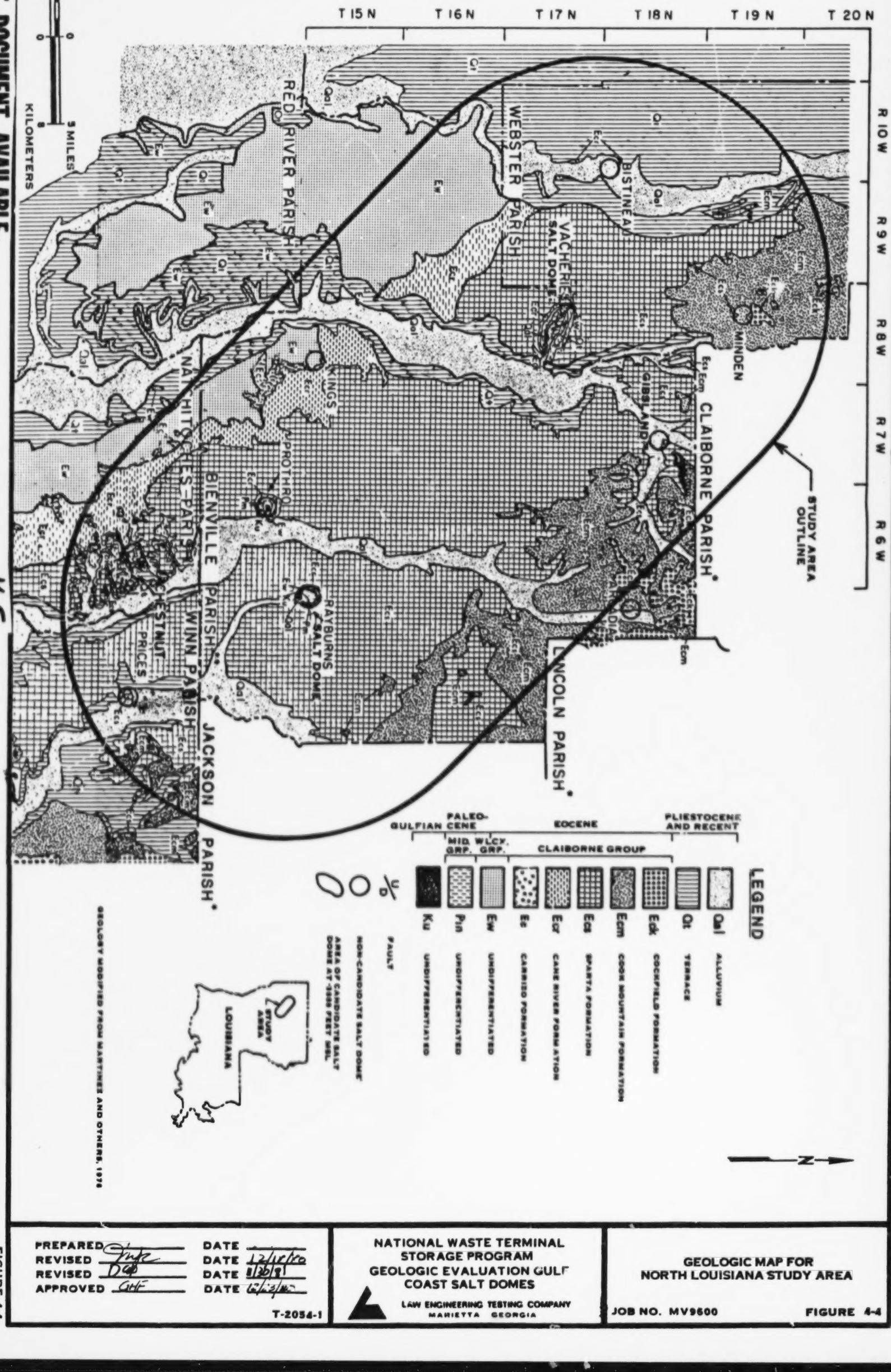

PREPARED	DATE	NATIONAL WASTE TERMINAL STORAGE PROGRAM GEOLOGIC EVALUATION GULF COAST SALT DOMES
REVISED	DATE 12/12/80	
REVISED	DATE 8/26/81	
APPROVED	DATE 6/12/81	LAW ENGINEERING TESTING COMPANY MARIETTA GEORGIA
T-2054-1		JOB NO. MV9600 FIGURE 4-4

GEOLOGIC MAP FOR NORTH LOUISIANA STUDY AREA

FIGURE 4-4

corner. Quaternary deposits and the Sparta Formation supply most of the ground-water discharge to streams.

In the East Texas Study Area, recharge to the Upper Cretaceous deposits occurs north of the study area where units are exposed at the surface and can be replenished by rainfall. After the rainfall infiltrates into the aquifers it flows south-to-southeastward through the study area. Recharge to Tertiary and Quaternary deposits exposed in the study area (Figure 4-5) occurs directly from rainfall as well as leakage between aquifers in areas south of the outcrops. Water in these aquifers generally flows toward the Trinity River in a southeasterly direction.

4.2.1.1.3 Saline Ground-Water Occurrence - In the Mississippi Study Area, the interface between fresh and saline water occurs between elevations of 122 and 488 meters (400 and 1,600 ft) below mean sea level (MSL) (Figure 4-6). Depth to saline water is greatest in the southwestern part of the study area and is least in the northeastern part of the area. This interface is situated in the upper part of deposits of Miocene age in the vicinity of Richton and Cypress Creek Domes. The interface is situated near the base of the Miocene deposits elsewhere.

The freshwater base appears to be anomalously high in the area between Richton and Cypress Creek Domes. Several reasons for this can be hypothesized. Upward flow in this area may be bringing saline water up from deeper formations. Also, the dome may be acting as a barrier, preventing connate saline water from

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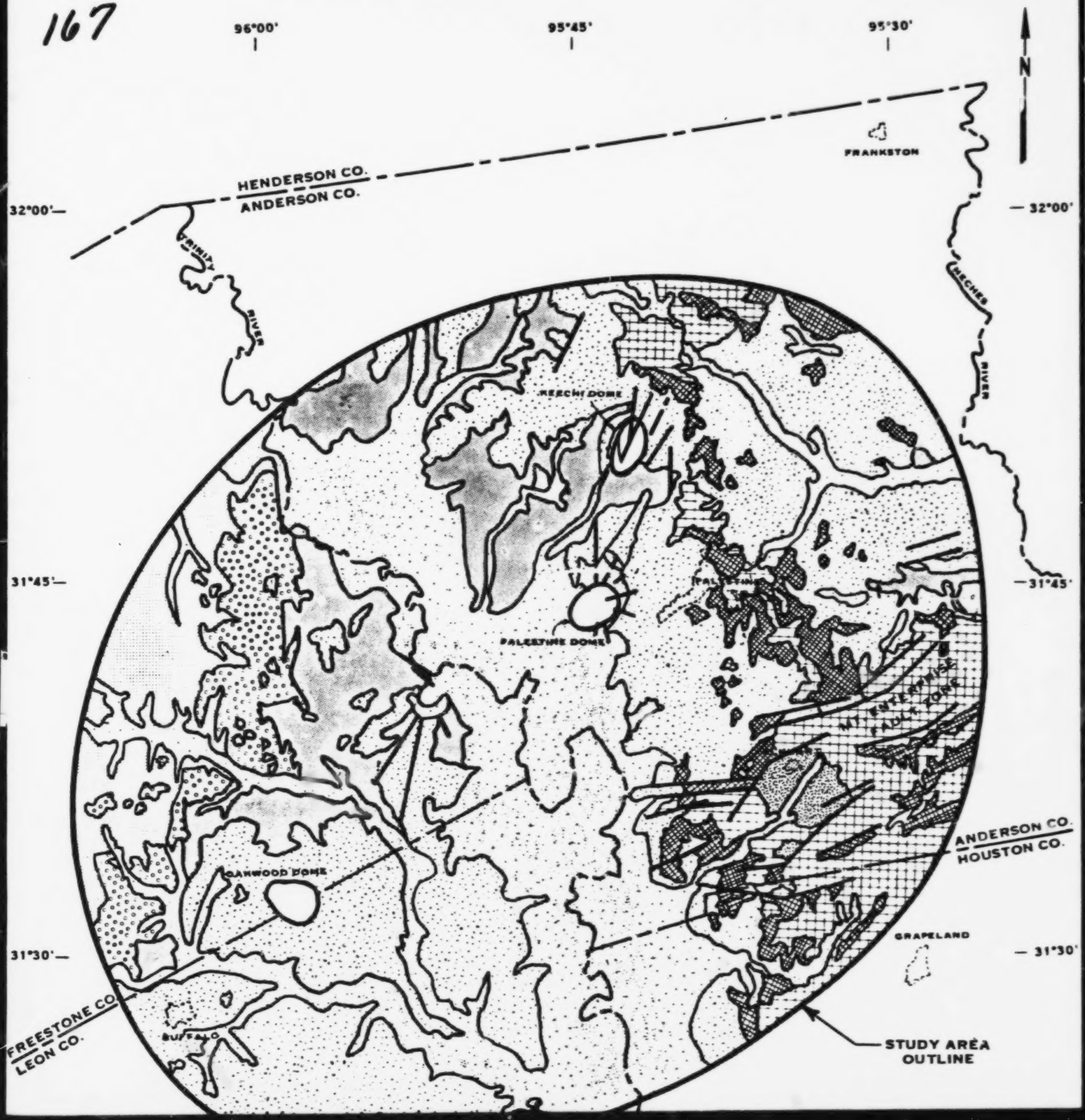

167-A

LEGEND

PLEISTOCENE AND RECENT
- QUATERNARY TERRACE AND RECENT FLOOD PLAIN

EOCENE
CLAIBORNE GROUP
- COOK MOUNTAIN FORMATION
- SPARTA FORMATION
- WECHES FORMATION
- QUEEN CITY FORMATION

PALEOCENE EOCENE
WILCOX GROUP CLAIBORNE
- REKLAW FORMATION
- CARRIZO FORMATION
- UNDIFFERENTIATED

FAULT

AREA OF CANDIDATE SALT DOME AT -3000 FEET MSL

STUDY AREA
TEXAS

GEOLOGY MODIFIED FROM BARROW, 1983

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REVISED		DATE	
APPROVED	RSM	DATE	9/30/81

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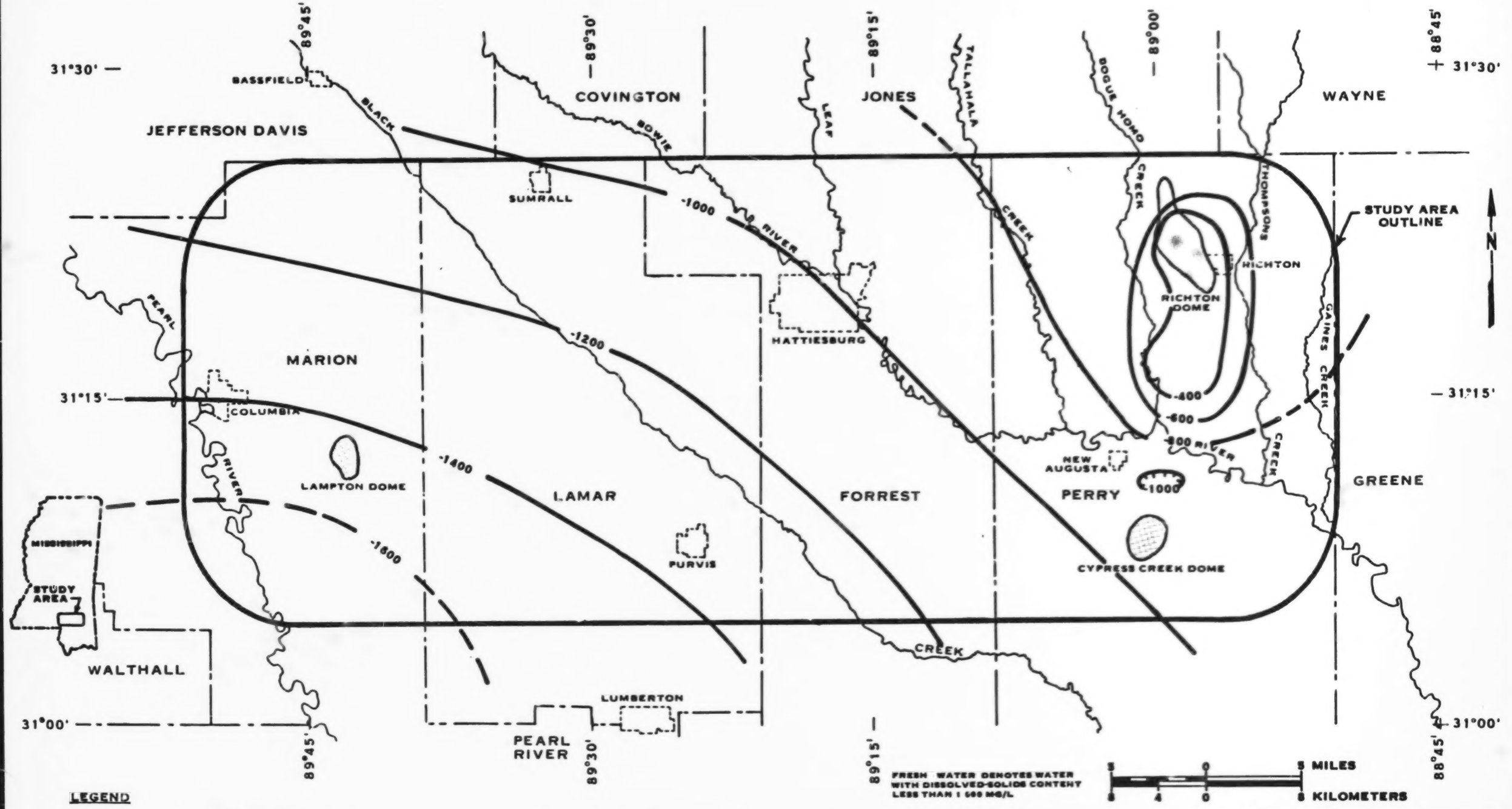
NATIONAL WASTE TERMINAL STORAGE PROGRAM
GEOLOGIC EVALUATION GULF COAST SALT DOMES

LAW ENGINEERING TESTING COMPANY
MARIETTA GEORGIA

GEOLOGIC MAP FOR EAST TEXAS STUDY AREA

JOB NO. MV9600

FIGURE 4-5



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SALT DOME SHOWING LOCATION OF -3000 FEET MEAN SEA LEVEL CONTOUR ON TOP OF SALT

-1000 BASE OF FRESH - WATER ZONE CONTOUR SHOWS ELEVATION OF BASE OF FRESH - WATER ZONE. DASHED WHERE INFERRED. CONTOUR INTERVAL 200 FEET. DATUM IS MEAN SEA LEVEL.

PREPARED	[illegible]	DATE	11/30
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APPROVED	RSM	DATE	9/28/81

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NATIONAL WASTE TERMINAL STORAGE PROGRAM
GEOLOGIC EVALUATION GULF COAST SALT DOMES
LAW ENGINEERING TESTING COMPANY
MARIETTA, GEORGIA

BASE OF FRESH-WATER IN MISSISSIPPI STUDY AREA

JOB NO. MV 9600 FIGURE 4-6

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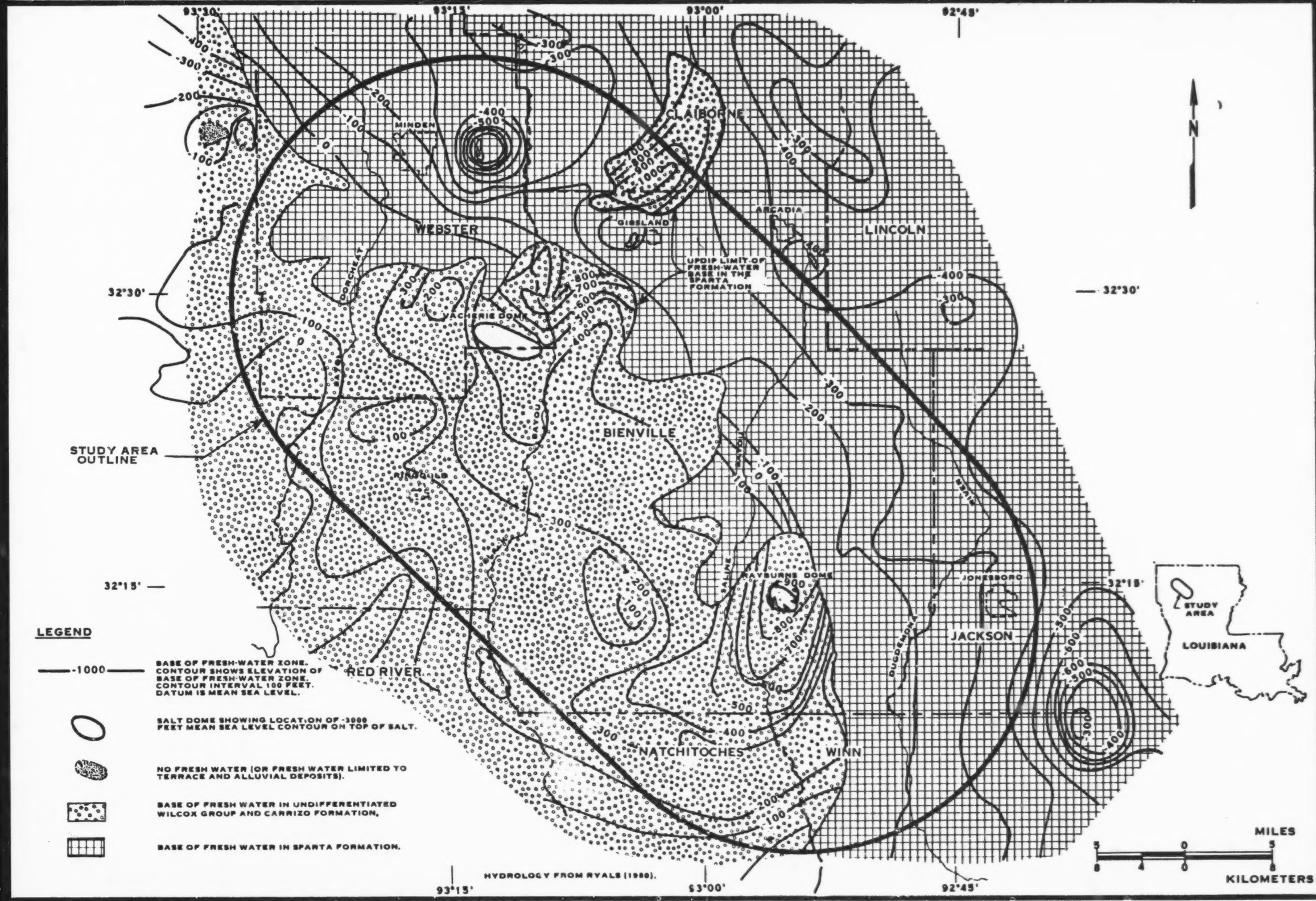
being flushed from the freshwater aquifers. Finally, saline water that occurs at high elevations and downgradient in Miocene deposits south of Richton Dome might be a result of salt dissolution at the dome. Further investigation is needed to explain the reasons for the high freshwater base south of Richton Dome.

In Louisiana, the interface between fresh and saline water occurs between 0 and -305 meters (0 and -1,000 ft) MSL in the undifferentiated Wilcox Group and Carrizo Formation in the western part of the study area, and between elevations of 30 and -274 meters (100 and -900 ft) MSL in the Sparta Formation in the eastern part of the study area (Figure 4-7). The freshwater base generally slopes eastward in both the Wilcox-Carrizo deposits and Sparta Formation. The clays of the Midway Group, underlying the Wilcox Group, retard downward circulation of fresh water in the western part of the study area. The clays and marls of the Cane River Formation, underlying the Sparta Formation, retard the downward circulation of fresh water in the eastern part of the study area.

Depth to saline water in Texas is greatest in the eastern and southeastern portions of the study area. Figure 4-8 shows the elevation of the base of fresh water in the study area.

4.2.1.2 Ground-Water Movement: Average ground-water velocities at various depths were determined for all three study areas during Area Characterization. Regional flow velocities were calculated from potentiometric surface maps, effective porosity, and



BASE OF FRESH-WATER IN NORTH LOUISIANA STUDY AREA

JOB NO. MV9600 FIGURE 4-7

NATIONAL WASTE TERMINAL STORAGE PROGRAM
GEOLOGIC EVALUATION GULF COAST SALT DOMES

LAW ENGINEERING TESTING COMPANY MARIETTA, GEORGIA

PREPARED	RSM	DATE 7/2/80
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FIGURE 4-7

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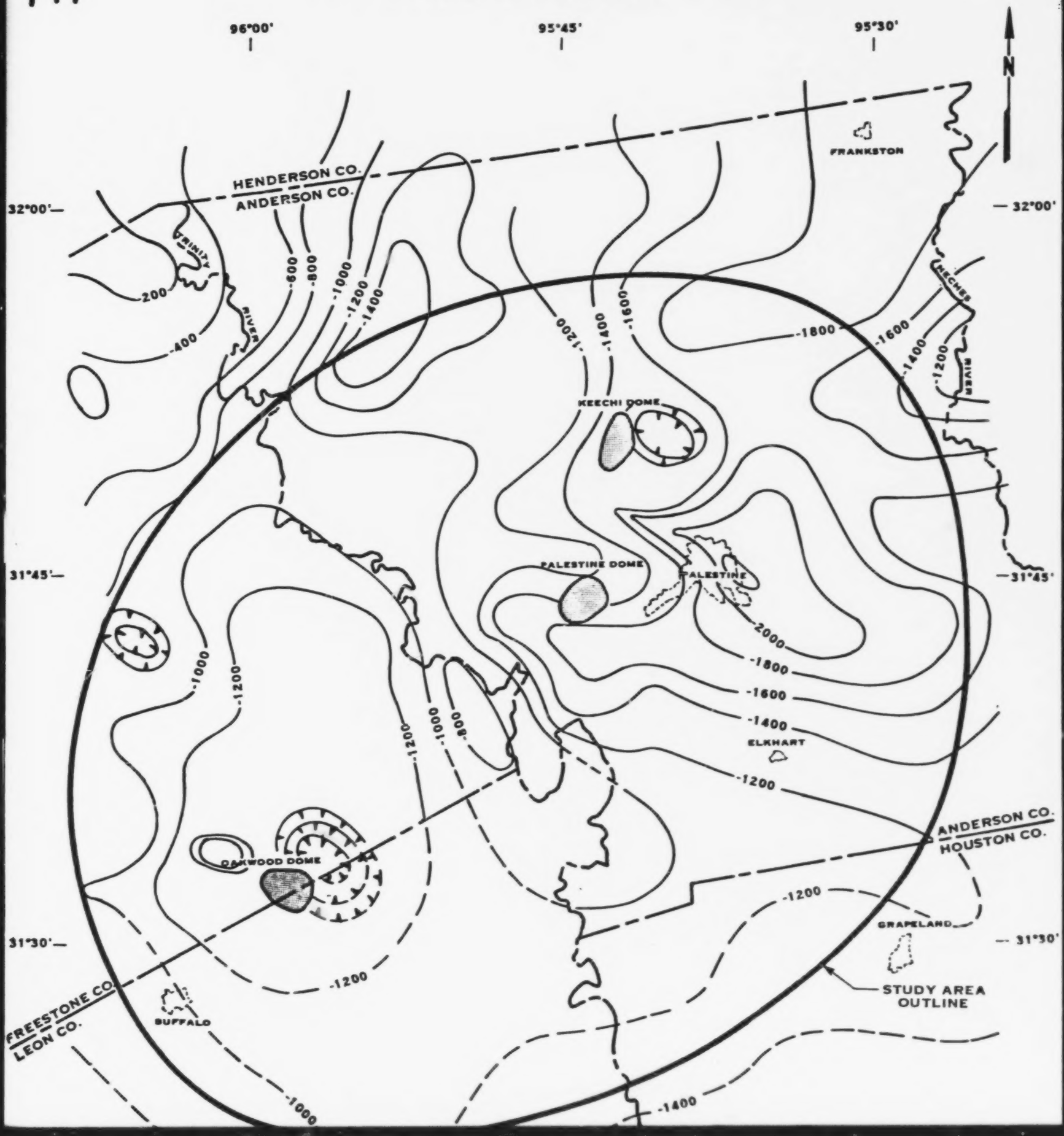

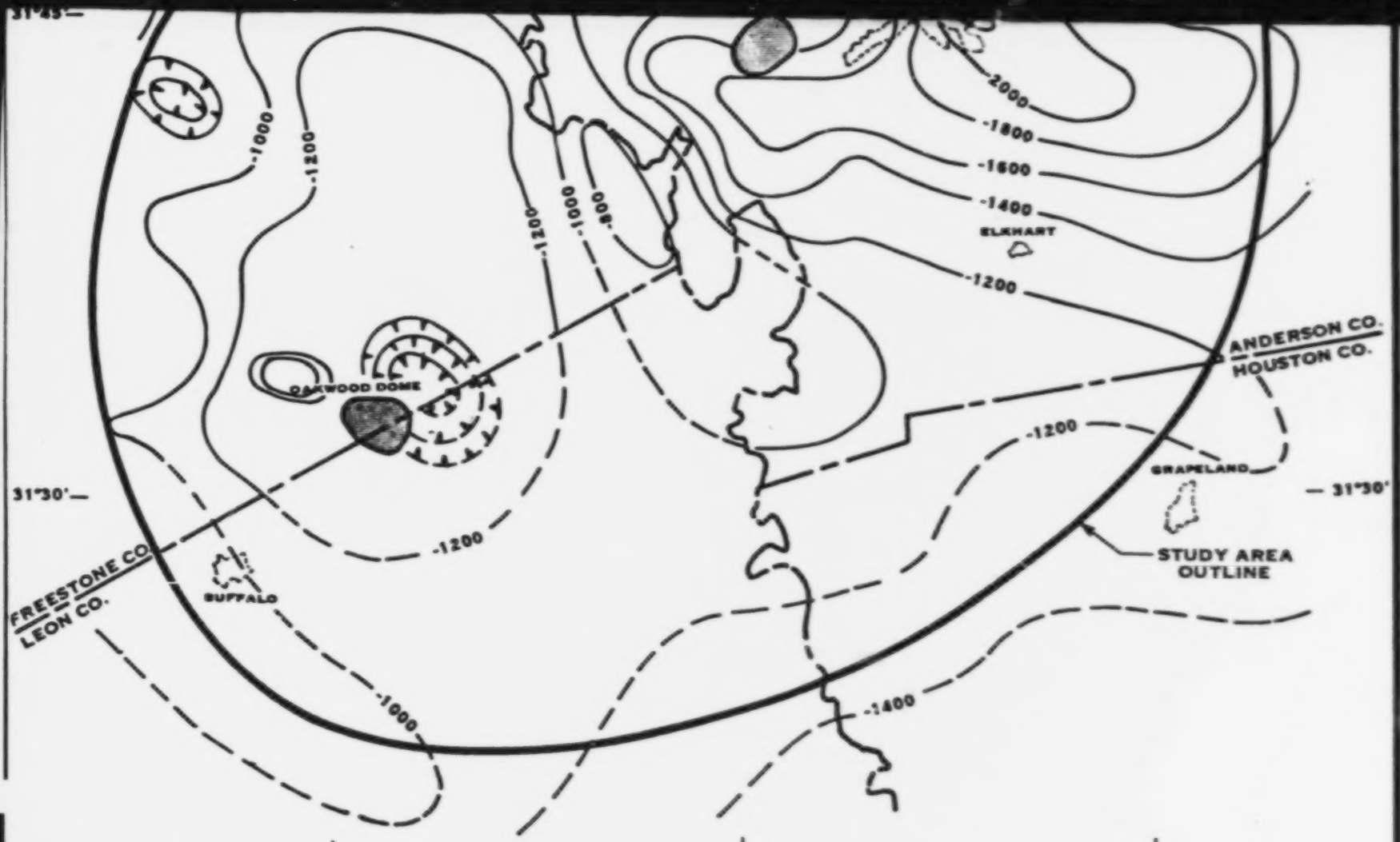

LEGEND

—-2000— BASE OF FRESH-WATER ZONE CONTOUR SHOWS ELEVATION OF BASE OF FRESH-WATER ZONE. CONTOUR INTERVAL 200 FEET. DASHED WHERE INFERRED. DATUM IS MEAN SEA LEVEL.

SALT DOME SHOWING LOCATION OF -2000 FEET MEAN SEA LEVEL CONTOUR ON TOP OF SALT.

ENCLOSED DEPRESSION

8 4 0 8 MILES

8 4 0 8 KILOMETERS

HYDROLOGY MODIFIED FROM SUTTON AND OTHERS, 1972

PREPARED LFB	DATE 9/28/81	NATIONAL WASTE TERMINAL STORAGE PROGRAM GEOLOGIC EVALUATION GULF COAST SALT DOMES
REVISED LFB	DATE 11/23/81	
REVISED	DATE	
APPROVED KSP	DATE 9/28/81	

T-2068-1

LAW ENGINEERING TESTING COMPANY
MARIETTA, GEORGIA

BASE OF FRESH WATER IN EAST TEXAS STUDY AREA

JOB NO. MV9700 FIGURE 4-8

171-A

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hydraulic conductivity estimates for the various geohydrologic units.

In the Mississippi Study Area, horizontal flow velocities determined for the Catahoula Formation and the lower Wilcox Group averaged about 5 and 3 m/yr (16 and 9 ft/yr), respectively, (Table 4-7). Ground-water velocities ranged from less than 0.3 m/yr (1 ft/yr) in the Claiborne Group in the west to about 5 m/yr (15 ft/yr) in the upper Wilcox Group in the east. Published data indicate that water movement in the Hattiesburg and Catahoula formations is generally downdip, following the regional trend of the sediments in the area (Taylor and others, 1968). Flow velocities computed by Taylor ranged from 0.3 to 49 m/yr (1 to 160 ft/yr). These data are in agreement with estimated water movement in the Hattiesburg and Catahoula Formations in the study area.

Horizontal ground-water velocities in Louisiana geologic deposits are variable in the study area (Table 4-7). The ground-water velocity in the Sparta Formation averages about 61 m/yr (200 ft/yr). The ground-water velocity in sand deposits in the lower part of the Wilcox Group, in areas where the Wilcox crops out, is about 3 m/yr (10 ft/yr). The ground-water velocity elsewhere in these deposits varies between 0.06 and 0.3 m/yr (0.2 and 1 ft/yr). The ground-water velocity in the upper part of the Wilcox Group is about 3 m/yr (10 ft/yr) throughout the study area. Flow velocities determined for the Nacatoch Formation range from 0.03 to 1.2 m/yr (0.1 to 4 ft/yr). The flow velocity in the Austin Group was computed to be about 2.4 m/yr (8 ft/yr).

TABLE 4-7.

GENERALIZED GROUND-WATER FLOW DIRECTIONS AND VELOCITIES IN STUDY AREAS

MISSISSIPPI STUDY AREA

AQUIFER	HORIZONTAL FLOW DIRECTION (MITIGATING FACTORS)	AVERAGE VELOCITY IN FEET/YEAR*
Alluvium and Terraces	From topographic highs to topographic lows	NA
Catahoula Formation	Southeast	16
Lower Claiborne and upper Wilcox Groups	South (Injection well stresses cause local high in southwest portion)	1-15
Lower Wilcox Group	South	9

NORTH LOUISIANA STUDY AREA

Alluvium and Terraces	From topographic highs to topographic lows	NA
Sparta Formation	East (Water withdrawals at Minden and Jonesboro cause local distortion)	200
Wilcox Group	Away from potentiometric high which extends northeast-southwest across center of study area (Natural recharge to outcropping deposits and injection well stresses cause high)	0.2-10
Nacatoch Formation	Northwest in northwest part of study area (Influenced by injection well stresses)	0.1-4
Austin Group	Southwest in southwest part of study area (Influenced by injection well stresses)	8

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TABLE 4-7.

GENERALIZED GROUND-WATER FLOW DIRECTIONS AND VELOCITIES IN STUDY AREAS (CONTINUED)

EAST TEXAS STUDY AREA

AQUIFER	HORIZONTAL FLOW DIRECTION (MITIGATING FACTORS)	AVERAGE VELOCITY IN FEET/YEAR
Sparta Formation	From topographic highs to topographic lows	NA
Queen City Formation	Toward Trinity River across center of study area	NA
Wilcox-Carrizo	Toward Trinity River across center of study area	15-18

*To convert to meters, multiply by 0.3048.

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Horizontal flow velocities were determined for the Wilcox-Carrizo Aquifer in the East Texas Study Area (Carr and others, 1980). The maximum ground-water velocity was estimated to be between 5 and 5.5 m/yr (15 and 18 ft/yr) across the center of the study area (Table 4-7).

4.2.1.3 Ground-Water Reservoir Uses: Ground-water reservoir uses were inventoried in all three study areas during Area Characterization.

In Mississippi, ground water is extensively utilized in the four-county study area. Municipal and industrial uses account for the largest withdrawals of ground water, with heaviest demand centered in the Hattiesburg area in Forrest County. Total ground pumpage for the county is about 106 million l/day (28 million gal/day), which is the highest ground-water use of the four counties in the study area.

Deep aquifers in Mississippi are used extensively for brine disposal in oil and gas fields. Disposal of brines is limited to formations already possessing high salinities, which include the Tuscaloosa, Eutaw, Wilcox, Sparta, Cook Mountain, and Cockfield. The heaviest concentrations of disposal wells are in the southwest corner of the study area. Most of the disposal wells in this area inject into the Cook Mountain Formation. The average injection rate for disposal wells in the study area in 1979 was approximately 9,462 l/day (2,500 gal/day) per well.

Ground water is used for a water supply throughout the North Louisiana Study Area. Municipal and industrial users account for most of the ground-water withdrawals, with the heaviest demands centered around Minden and Jonesboro. The Sparta Formation is the principal source for this supply. Total ground water withdrawal in the study area is about 197 million l/day (52 million gal/day).

Thirty-nine brine disposal wells and two chemical waste disposal wells are located in and around the North Louisiana Study Area. Disposal is generally into the Nacatoch and Tokio Formations from these wells. The closest disposal wells to Vacherie Dome are located approximately 4.8 km (3 mi) to the north and northeast of the dome. At Rayburn's Dome the closest disposal wells are 9.6 km (6 mi) to the east and southeast.

The largest ground-water withdrawals in Texas occur in southern Anderson County, south of Palestine. Ground-water withdrawal in Anderson County is about 23 million l/day (6 million gal/day). Increased utilization of surface water and the slowdown in industrial activity has contributed to the reduced growth in demand for ground-water supplies.

A total of 191 disposal wells were identified in the East Texas Study Area. The largest concentration of these wells is located in southern Anderson County. Injection is generally into the beds of the Wilcox and Woodbine Groups and the Carrizo Formation.

4.2.2 DOMAL AREA GEOHYDROLOGIC SETTINGS: The sequence of hydrogeologic units at Richton, Cypress Creek, and Lampton Domes in

Mississippi is similar to that which occurs regionally. Tertiary deposits include the Midway, Wilcox, Claiborne, Jackson, and Vicksburg Groups; and the Chickasawhay, Catahoula, and Hattiesburg Formations. These are overlain by the Citronelle, terrace deposits, and alluvium. The Hattiesburg Formation is the basal unit directly overlying caprock at Richton and Cypress Creek Domes. At Lampton Dome the Chickasawhay Formation overlies the caprock.

In Louisiana the sequence of hydrogeologic units near Rayburn's and Vacherie Domes includes the Upper Cretaceous, Tertiary, and Quaternary deposits above the undifferentiated Tuscaloosa and Eagle Ford Groups.

The sequence of hydrogeologic units at Oakwood and Keechi Domes in Texas is similar to that which occurs regionally. Upper Cretaceous deposits include, in ascending order, the Woodbine, Eagle Ford, Austin, and Taylor Groups and the Nacatoch Formation of the Navarro Group. These are overlain by Tertiary deposits which include, in ascending order, the Midway, Wilcox, and Claiborne Groups. Quaternary alluvial floodplain and terrace deposits complete the stratigraphic sequence; however, these deposits are not present everywhere over the domes.

Hydrogeologic cross sections were constructed through each of the candidate domes (Figures 4-9 through 4-15). Illustrated for each dome are geologic units and their water-transmitting properties and the base of fresh water.

NORTHEAST

SOUTHWEST

EXPLORO NO. 6 MASONITE

MINSEARCH NO. B-7 RIDGWAY

EXPLORO NO. 4 MASONITE

SHELL NO. 23-7 MASONITE

DOE NO. MRIG-8 MASONITE

MINSEARCH NO. B-8 RIDGWAY

SHELL NO. 1 MASONITE

MINSEARCH NO. 1 SMITH

DOE NO. MRIG-10 MASONITE

DOE NO. MRIH-11A SMITH

SEA LEVEL

FEET

METERS

1000
0
-1000
-2000
-3000
-4000
-5000
-6000

-500
-1000
-1500

MIOCENE AGE AND YOUNGER DEPOSITS (UNDIFF.)

VICKSBURG AND JACKSON GROUPS (UNDIFF.)

COCKFIELD FORMATION

COOK MOUNTAIN FORMATION

SPARTA FORMATION

ZILPHA, WINONA AND TALLAHATTA FORMATIONS (UNDIFF.)

CLAIBORNE GROUP

RICHTON DOME

WILCOX GROUP

MIDWAY GROUP

UPPER CRETACEOUS SEDIMENTS (NOT STUDIED)

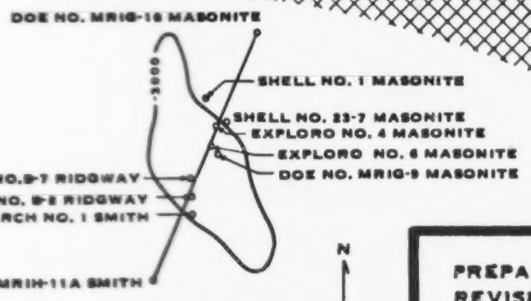
VERTICAL EXAGGERATION X 4

4000 0 4000 FEET

1000 0 1000 METERS

LEGEND

- GEOLOGIC UNITS THAT MAY HAVE GOOD WATER TRANSMITTING PROPERTIES
- GEOLOGIC UNITS THAT GENERALLY HAVE POOR WATER TRANSMITTING PROPERTIES
- CAPROCK
- SALT
- TOP OF LOGGED INTERVAL FOR GEOLOGIC INTERPRETATION
- FORMATION CONTACT
- INFERRED FORMATION CONTACT
- APPROXIMATE WATER TABLE CONFIGURATION
- APPROXIMATE BASE OF FRESH WATER



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NATIONAL WASTE TERMINAL STORAGE PROGRAM
GEOLOGIC EVALUATION GULF COAST SALT DOMES

LAW ENGINEERING TESTING COMPANY
MARIETTA, GEORGIA

HYDROGEOLOGIC CROSS-SECTION THROUGH RICHTON DOME

JOB NO. MV9700

FIGURE 4-9

BEST DOCUMENT AVAILABLE

NORTH

DOE NO. MCCG-2 USA

SHELL NO. 10-5 USA

DOE NO. MCCG-1 USA

PHILLIPS NO. 1 NEWMAN

SOUTH

DOE NO. MCCH-3B USA

MIOCENE AGE AND YOUNGER DEPOSITS (UNDIFF.)

VICKSBURG AND JACKSON GROUPS (UNDIFF.)

COCKFIELD FORMATION

COOK MOUNTAIN FORMATION

SPARTA FORMATION

ZILPHA, WINONA AND TALLAHATTA FORMATIONS (UNDIFF.)

CLAIBORNE GROUP

CYPRESS CREEK DOME

WILCOX GROUP

MIDWAY GROUP

UPPER CRETACEOUS SEDIMENTS (NOT STUDIED)

VERTICAL EXAGGERATION X 4

METERS: 500, 0, -500, -1000, -1500, -2000, -2500

FEET: 500, SEA LEVEL, -1000, -2000, -3000, -4000, -5000, -6000, -7000, -8000, -9000

4000 0 4000 FEET

1000 0 1000 METERS

DOE NO. MCCG-2 USA

DOE NO. MCCG-1 USA

SHELL NO. 10-5 USA

PHILLIPS NO. 1 NEWMAN

DOE NO. MCCH-3B USA

0 2 MILES

0 3 KILOMETERS

N

LINE OF SECTION

LEGEND

- GEOLOGIC UNITS THAT MAY HAVE GOOD WATER-TRANSMITTING PROPERTIES
- GEOLOGIC UNITS THAT GENERALLY HAVE POOR WATER-TRANSMITTING PROPERTIES
- CAPROCK
- SALT
- TOP OF LOGGED INTERVAL FOR GEOLOGICAL INTERPRETATION
- FAULT, DASHED WHERE INFERRED
- FORMATION CONTACT
- INFERRED FORMATION CONTACT
- WATER TABLE CONFIGURATION APPROXIMATE
- BASE OF FRESH WATER APPROXIMATE

HYDROGEOLOGIC CROSS-SECTION THROUGH CYPRESS CREEK DOME

FIGURE 4-10

JOB NO. MV9600

NATIONAL WASTE TERMINAL STORAGE PROGRAM
GEOLOGIC EVALUATION GULF COAST SALT DOMES

LAW ENGINEERING TESTING COMPANY MARIETTA, GEORGIA

	DATE
PREPARED	9/29/81
REVISED	11/3/81
REVISED	
APPROVED	9/28/81

T-1918-1

FIGURE 4-10

BEST DOCUMENT AVAILABLE

NORTHWEST

SOUTHEAST

EXPLORO NO. 1 HURST

EXPLORO NO. 4 BRADSHAW

EXPLORO NO. 2 BRADSHAW

GULF NO. 4 BRADSHAW

GULF NO. 3 BRADSHAW

PARKER NO. 1 SIMMONS

DOE NO. MH-3 MASONITE

SEA LEVEL

FEET

METERS

500

0

-1000

-500

-2000

-3000

-1000

-4000

-1500

-5000

-2000

-6000

-7000

MIOCENE AGE AND YOUNGER DEPOSITS (UNDIFF.)

VICKSBURG AND JACKSON GROUPS (UNDIFF.)

CLAIBORNE GROUP

COCKFIELD FORMATION

COOK MOUNTAIN FORMATION

SPARTA FORMATION

ZILPHA, WINONA AND TALLAHATTA FORMATIONS (UNDIFF.)

LAMPTON DOME

WILCOX GROUP

MIDWAY GROUP

UPPER CRETACEOUS SEDIMENTS (NOT STUDIED)

LEGEND

- GEOLOGIC UNITS THAT MAY HAVE GOOD WATER TRANSMITTING PROPERTIES
- GEOLOGIC UNITS THAT GENERALLY HAVE POOR WATER TRANSMITTING PROPERTIES
- CAPROCK
- SALT
- TOP OF LOGGED INTERVAL FOR GEOLOGICAL INTERPRETATION
- FAULT, DASHED WHERE INFERRED
- FORMATION CONTACT
- INFERRED FORMATION CONTACT
- WATER TABLE CONFIGURATION APPROXIMATE
- BASE OF FRESH WATER APPROXIMATE

VERTICAL EXAGGERATION X 4

4000 0 4000 FEET

1000 0 1000 METERS

PARKER NO.1 SIMMONS

EXPLORO NO.1 HURST

EXPLORO NO.4 BRADSHAW

EXPLORO NO.2 BRADSHAW

GULF NO.4 BRADSHAW

GULF NO.3 BRADSHAW

DOE NO. MH-3 MASONITE

N

0 2 MILES

0 3 KILOMETERS

LINE OF SECTION

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NATIONAL WASTE TERMINAL STORAGE PROGRAM
GEOLOGIC EVALUATION GULF COAST SALT DOMES
LAW ENGINEERING TESTING COMPANY
MARIETTA, GEORGIA

HYDROGEOLOGIC CROSS-SECTION THROUGH LAMPTON DOME

JOB NO. MV9700

FIGURE 4-11

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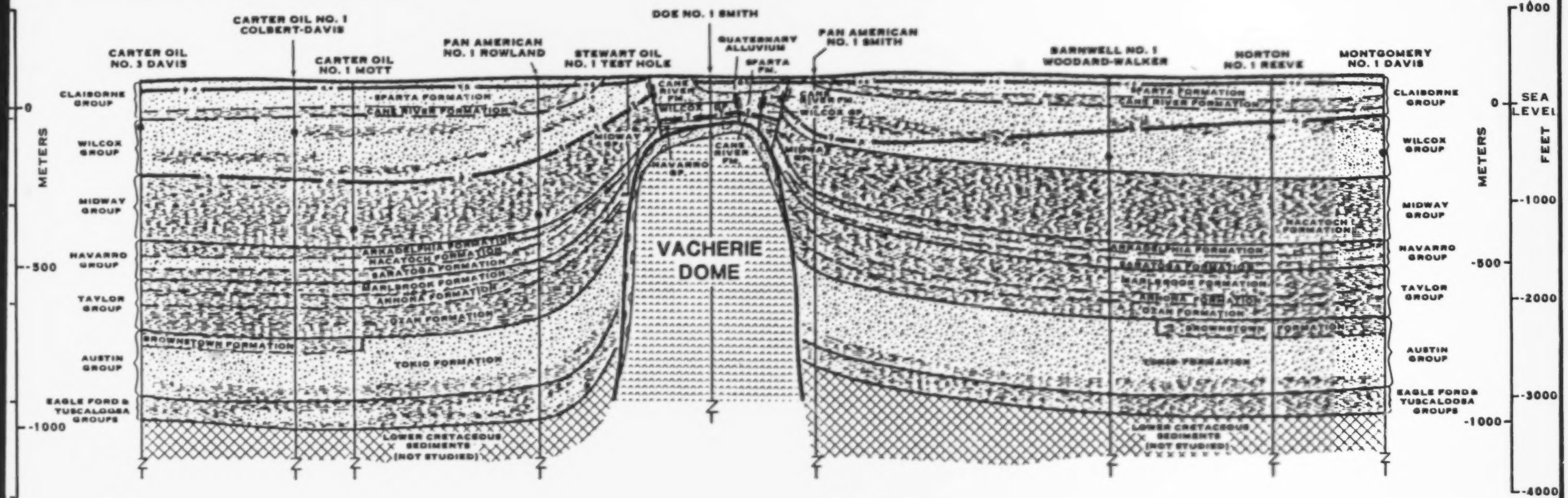
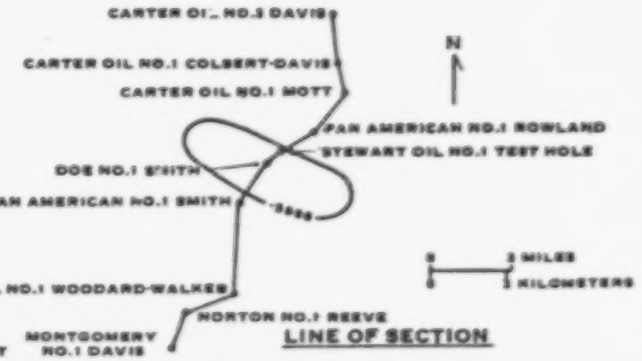
NORTHEAST

SOUTHWEST



VERTICAL EXAGGERATION X 4



4000 0 4000 FEET

1000 0 1000 METERS

EGEND:

- GEOLOGIC UNITS THAT MAY HAVE GOOD WATER TRANSMITTING PROPERTIES.
- GEOLOGIC UNITS THAT GENERALLY HAVE POOR WATER TRANSMITTING PROPERTIES.
- CAPROCK
- SALT
- TOP OF LOGGED INTERVAL FOR GEOLOGIC INTERPRETATION.
- FAULT
- FORMATION CONTACT
- INFERRED FORMATION CONTACT
- APPROXIMATE WATER TABLE CONFIGURATION
- APPROXIMATE BASE OF FRESH WATER

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NATIONAL WASTE TERMINAL STORAGE PROGRAM
GEOLOGIC EVALUATION GULF COAST SALT DOMES
LAW ENGINEERING TESTING COMPANY
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HYDROGEOLOGIC CROSS-SECTION THROUGH VACHERIE DOME

JOB NO. MV9600

FIGURE 4-12

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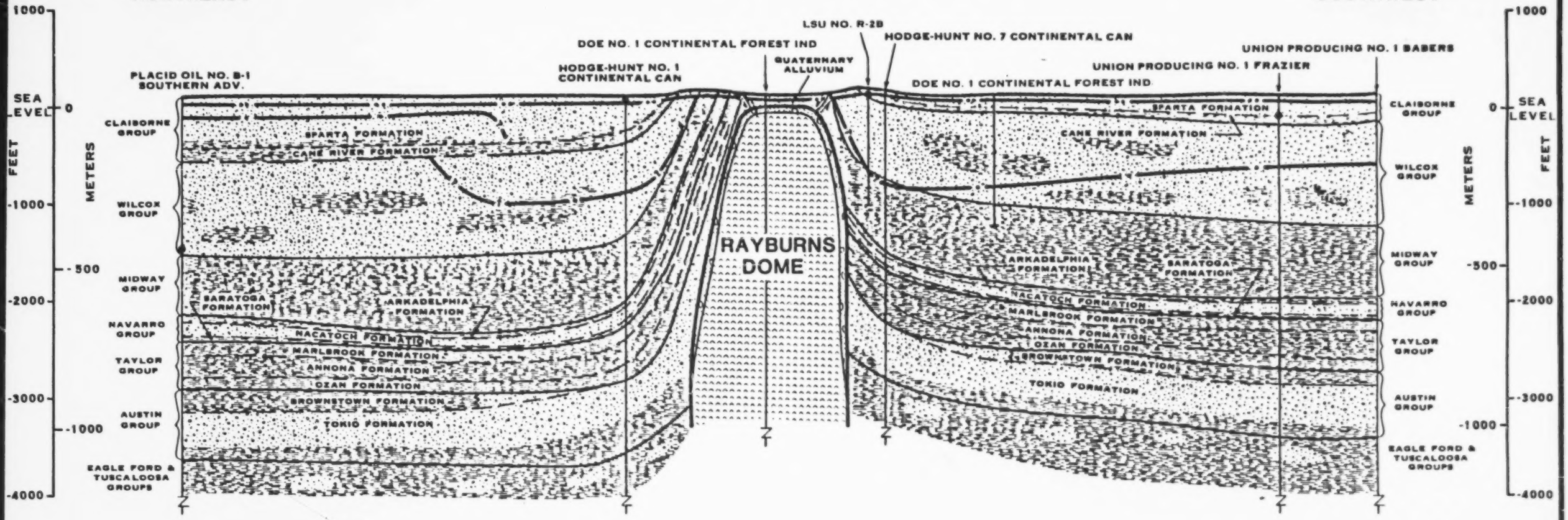
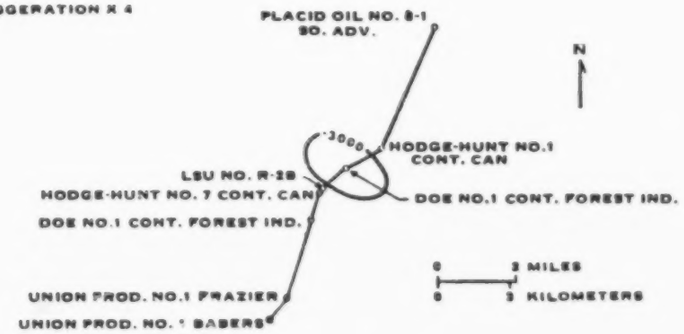


VERTICAL EXAGGERATION X 4

LEGEND

- GEOLOGIC UNITS THAT MAY HAVE GOOD WATER TRANSMITTING PROPERTIES
- GEOLOGIC UNITS THAT GENERALLY HAVE POOR WATER TRANSMITTING PROPERTIES
- CAPROCK
- SALT
- TOP OF LOGGED INTERVAL FOR GEOLOGIC INTERPRETATION
- FAULT
- FORMATION CONTACT
- INFERRED FORMATION CONTACT
- APPROXIMATE WATER TABLE CONFIGURATION
- APPROXIMATE BASE OF FRESH WATER



4000 0 4000 FEET
1000 0 1000 METERS

LINE OF SECTION

PREPARED	LRR	DATE 9/28/81
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NATIONAL WASTE TERMINAL STORAGE PROGRAM
GEOLOGIC EVALUATION GULF COAST SALT DOMES
LAW ENGINEERING TESTING COMPANY
MARIETTA, GEORGIA

HYDROGEOLOGIC CROSS-SECTION THROUGH RAYBURNS DOME

JOB NO. MV9600 FIGURE 4-13

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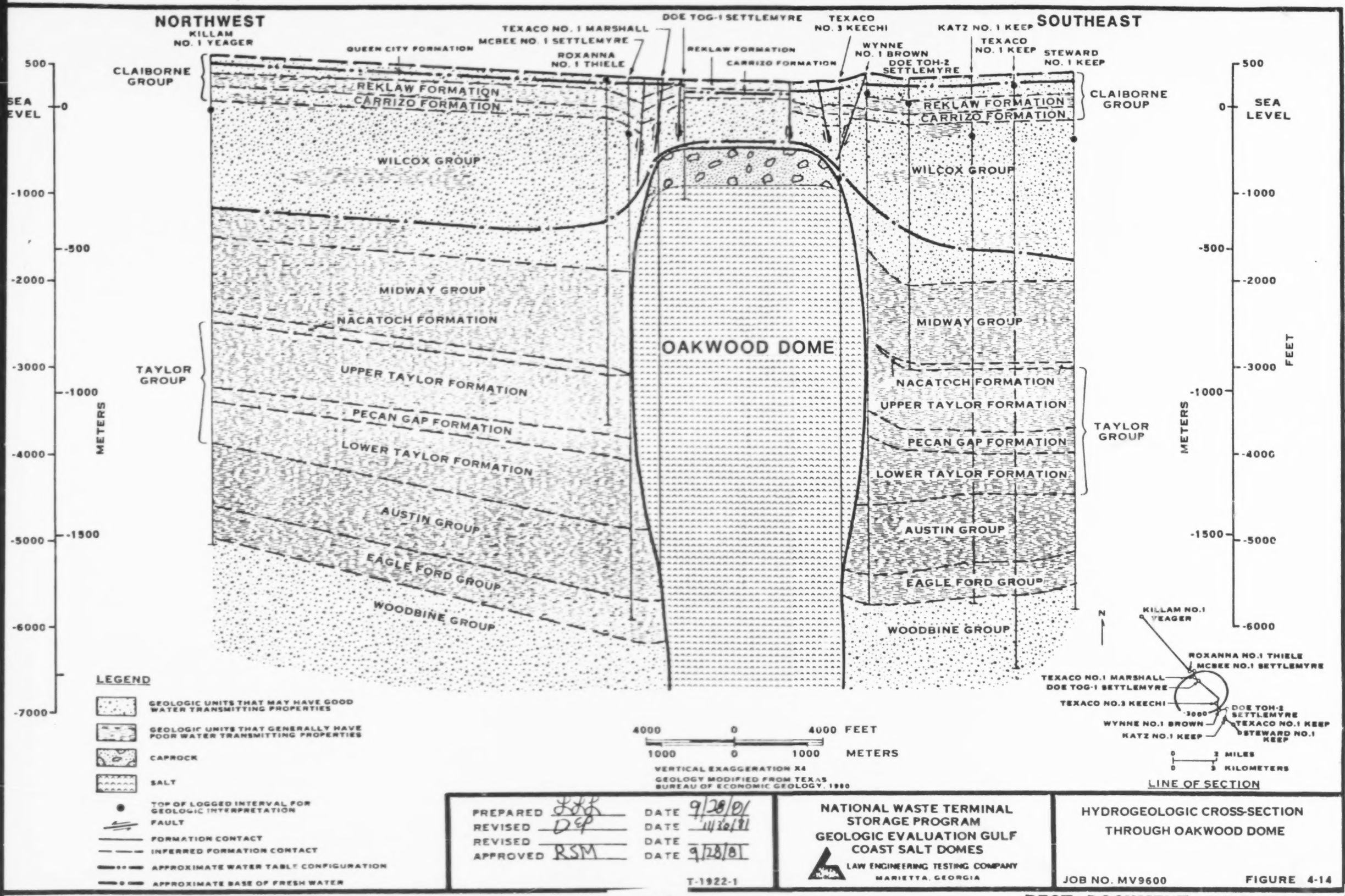

PREPARED LLL	DATE 9/28/01	NATIONAL WASTE TERMINAL STORAGE PROGRAM GEOLOGIC EVALUATION GULF COAST SALT DOMES
REVISED DEP	DATE 11/26/01	LAW ENGINEERING TESTING COMPANY MARIETTA, GEORGIA
REVISED	DATE	
APPROVED RSM	DATE 9/28/01	

T-1922-1

HYDROGEOLOGIC CROSS-SECTION THROUGH OAKWOOD DOME

JOB NO. MV9600 FIGURE 4-14

BEST DOCUMENT AVAILABLE

NORTH

SOUTH

HUMBLE NO. C-1 SAMPSON

MEADOWS NO. 1 CONCORD

ANDRADE NO. 1 FITZGERALD

NAVARRO NO. 4 GREENWOOD

LA RUE NO. 1 JERNIGAN

NAVARRO NO. 3 GREENWOOD

NAVARRO NO. 2 GREENWOOD

NAVARRO NO. 1 GREENWOOD

NAVARRO NO. 1 BARRETT

PRODUCERS NO. 3 BARRETT AND GREENWOOD

FARISH III NO. 1 WAITS

OLSON NO. 1 JORDAN

CLAIBORNE GROUP

WILCOX GROUP

MIDWAY GROUP

NACATOCH FORMATION

TAYLOR GROUP

AUSTIN GROUP

EAGLE FORD GROUP

WOODBINE GROUP

KEECHI DOME

MIDWAY

NACATOCH

TAYLOR

LOWER CRETACEOUS SEDIMENTS (NOT STUDIED)

EAGLE FORD GROUP

METERS

FEET

SEA LEVEL

0

-500

-1000

-1500

-2000

-3000

-4000

-5000

-6000

LEGEND:

GEOLOGIC UNITS THAT MAY HAVE GOOD WATER TRANSMITTING PROPERTIES.

GEOLOGIC UNITS THAT GENERALLY HAVE POOR WATER TRANSMITTING PROPERTIES.

CAPROCK

SALT

TOP OF LOGGED INTERVAL FOR GEOLOGIC INTERPRETATION.

FAULT, DASHED WHERE INFERRED

FORMATION CONTACT

INFERRED FORMATION CONTACT

APPROXIMATE WATER TABLE CONFIGURATION

APPROXIMATE BASE OF FRESH WATER

4000 0 4000 FEET

1000 0 1000 METERS

VERTICAL EXAGGERATION X4

GEOLOGY MODIFIED FROM TEXAS BUREAU OF ECONOMIC GEOLOGY, 1980

ANDRADE NO.1 FITZGERALD

HUMBLE NO.C-1 SAMPSON

MEADOWS NO.1 CONCORD

LA RUE NO.1 JERNIGAN

NAVARRO NO.4 GREENWOOD

NAVARRO NO.3 GREENWOOD

NAVARRO NO.2 GREENWOOD

NAVARRO NO.1 GREENWOOD

NAVARRO NO.1 BARRETT

PRODUCERS NO.3 BARRETT AND GREENWOOD

FARISH III NO.1 WAITS

OLSON NO.1 JORDAN

5000

N

LINE OF SECTION

0 2 MILES

0 3 KILOMETERS

PREPARED SSL DATE 9/28/81

REVISED DAP DATE 11/30/81

REVISED ____ DATE ____

APPROVED RSM DATE 9/28/81

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NATIONAL WASTE TERMINAL STORAGE PROGRAM

GEOLOGIC EVALUATION GULF COAST SALT DOMES

LAW ENGINEERING TESTING COMPANY MARIETTA, GEORGIA

HYDROGEOLOGIC CROSS-SECTION THROUGH KEECHI DOME

JOB NO. MV9600

FIGURE 4-15

BEST DOCUMENT AVAILABLE

4.2.2.1 Water-Transmitting Properties of Domal Caprock: The hydraulic properties of caprock were determined at two domes, Richton and Cypress Creek, during Area Characterization studies (Table 4-8). The hydraulic conductivity of the caprock at Richton Dome was approximately 0.2 m/day (0.8 ft/day), and at Cypress Creek Dome it was 0.1 m/day (0.36 ft/day). The hydraulic conductivity of the caprock at the caprock-salt interface at Richton Dome was similar to the hydraulic conductivity of the caprock, while at Cypress Creek Dome the hydraulic conductivity of the caprock at the caprock-salt interface was approximately two orders of magnitude less than that of the caprock.

Ground-water movement in the caprock is believed to be primarily through fractures, joints, and solution channels. Problems in maintaining water circulation during drilling operations at both Richton and Cypress Creek Domes suggest that solution channels exist and that secondary porosity features are probable. Further investigation is needed to define the hydraulic properties of all the domes selected for further study.

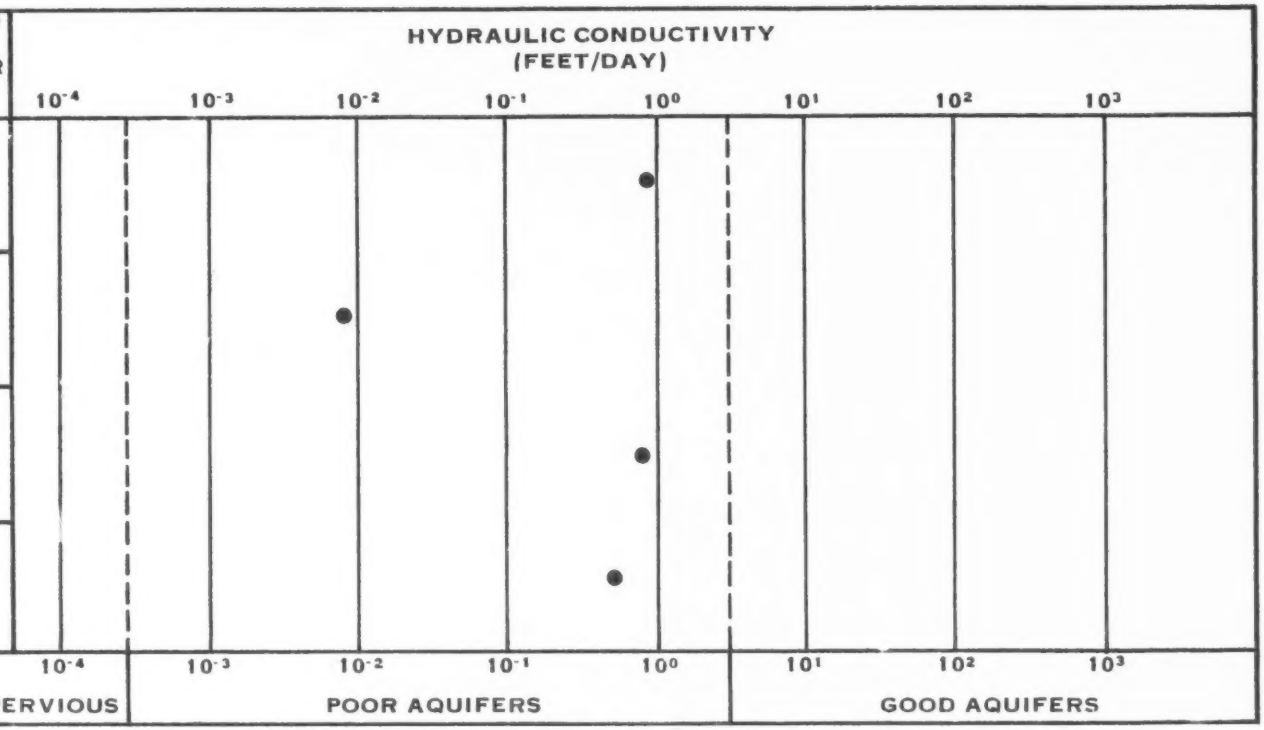
4.2.3 GROUND-WATER FLOW MODELING

4.2.3.1 One-Dimensional Vertical Ground-Water Flow Models for Domal Areas: A one-dimensional vertical ground-water flow model was developed for all of the candidate domes. These models were used to investigate average vertical ground-water flow times from various depths in the geologic section to the base of fresh water. The principal objective of the analysis was to ascertain if significant differences between vertical ground-water flow

TABLE 4-8.

AQUIFER TEST SUMMARY FOR CAPROCK

GEOLOGIC UNIT	NUMBER OF AQUIFER TEST WELLS	HYDRAULIC CONDUCTIVITY (FEET/DAY)
OPEN HOLE COMPLETED IN CYPRESS CREEK SALT DOME CAPROCK	1	
CYPRESS CREEK SALT DOME CAPROCK INTERFACE	1	
OPEN HOLE COMPLETED IN RICHTON SALT DOME CAPROCK	1	
RICHTON SALT DOME CAPROCK INTERFACE	1	



* MODIFIED FROM FAIR AND GEYER, 1958

times exist among the candidate domes. The most significant variables available from measured data were vertical head differences and the ratio of the length of the travel path in shale or clay to the total travel path length. The model used assumed ranges of permeabilities of the intergranular pore spaces in the geologic formations. Flow through secondary openings such as joints or fractures was not considered in this analysis.

The results of the analyses indicate that the estimated average vertical ground-water flow times are long and that significant differences in these flow times among the candidate domes cannot be substantiated with the existing data. Minimum vertical flow times at the domes varied between approximately 31,000 years from a point 152 meters (500 ft) below the base of fresh water at Lampton Dome, to approximately 360,000 years from a point 610 meters (2,000 ft) below the base of fresh water at Cypress Creek Dome (Slaughter, 1981).

4.3 GEOCHEMISTRY

Geochemical investigations within the study areas provide data for the characterization of water and rock chemical interactions and for identifying the potential for radionuclide retardation along ground-water flow paths.

4.3.1 CHEMICAL INTERACTION: Regional and domal area surface-water and ground-water chemistry were investigated and characterized for each study area. Analysis and characterization of surface- and ground-water chemistry identified regional types of water, trends in water chemistry, and cultural impacts on water chemistry within each study area.

Chemical interactions between ground water and ground-water reservoir materials were also investigated and characterized for each study area.

4.3.1.1 Surface-Water Chemistry: Surface waters within the Mississippi Study Area are generally a dilute calcium bicarbonate or sodium bicarbonate water (the principal ions in solution are calcium or sodium and bicarbonate). Total dissolved-solids concentration in the water is generally less than 200, although exceptions are common. The pH of the water is generally less than 7.0 standard units (s.u.).

Field measurements and chemical analyses of surface waters in the Cypress Creek, Lampton, and Richton Dome areas indicate that these waters are similar in chemistry to surface waters found regionally.

The chemical character of surface waters in the Louisiana Study Area is highly variable. Calcium, sodium, and bicarbonate are the predominant constituents in water from some streams in the study area, whereas sodium and chloride are the predominant constituents in water from other streams.

Field measurements and chemical analyses of surface waters in the Vacherie and Rayburn's Dome areas indicate that these waters may be anomalous in their chemistry. Variations by a factor of 10 were detected in field measurements of total dissolved solids concentrations at several sites around Vacherie Dome. Water samples analyzed by the USGS indicated a trend toward increasing downstream chloride content of water from streams overlying Vacherie Dome, and abnormally high concentrations of chloride in surface waters south of Rayburn's Dome (Ryals and Hosman, 1980).

Surface waters in the Trinity River Basin in the East Texas Study Area are mostly a calcium bicarbonate type. The total concentration of dissolved solids in the water is generally less than 500 mg/l (500 parts per million (ppm)), although concentrations exceeding 1,000 mg/l (1,000 ppm) are common and a few exceeded 10,000 mg/l (10,000 ppm). Unlined storage pits for the disposal of saline water that may leak into creeks in the study area, and sewage effluent discharged into streams during low-flow periods may account for the high total dissolved-solids values reported. The pH of the surface waters in the basin tends to be slightly alkaline in the major streams and slightly acidic in small creeks and tributaries.

Results of USGS field measurements and chemical analyses in the vicinity of Oakwood and Keechi Domes indicate that surface

waters are acidic and are low in total dissolved solids (Rawson, 1974). Specific conductance of the waters range between 150 and 700 micromhos per centimeter. Reported pH values of the waters range between 3.4 and 7.4 s.u.. Chemical analyses of water samples indicated that surface waters around Oakwood Dome are a sodium sulfate chloride type. The water chemistry is different than that found at regional data collection sites where surface waters are generally a calcium bicarbonate type.

4.3.1.2 Ground-water Chemistry: The chemical character of ground water in the Mississippi Study Area changes with increasing depth. Fresh water in shallow surficial deposits is mostly a calcium bicarbonate type. Fresh water in deposits of Miocene age is generally a dilute sodium bicarbonate type. Underlying saline water may be characterized as a sodium chloride type, with dissolved solids and salinity generally increasing with depth.

A chemical anomaly occurs in the fresh-water zone in deposits of Miocene age north of Cypress Creek Dome between the dome and the Leaf River. Total dissolved-solids concentration of the ground water in this area is approximately 500 mg/l (500 ppm). The water can be described as a sodium chloride type. Total dissolved-solids content of the ground water in surrounding areas is generally less than 200 mg/l (200 ppm) and can be described as a sodium bicarbonate type. Additional investigations are needed to confirm and identify the origin, and delineate the extent of this anomaly.

Gas content analyses were run on water samples obtained at selected sites in the Mississippi Study Area. Samples were taken from the Cook Mountain, Sparta, and Wilcox Formations. Methane, ethane, and hydrogen gas were detected in most samples.

The chemical character of ground water in the North Louisiana Study Area also changes with increasing depth. Calcium and bicarbonate are generally the predominant constituents in water from surficial Quaternary deposits. Sodium and bicarbonate are typically the dominant constituents in fresh water from the Sparta Formation. Sodium and chloride are the dominant constituents in the saline water that underlies the fresh water. The dissolved-solids content of the saline water generally increases with depth.

The salinity of water in the Wilcox Group in the vicinity of Vacherie Dome has been investigated by Martinez and others (1979). High concentrations of total dissolved solids were identified in the water in these deposits on the east side of the dome. This salinity concentration has tentatively been attributed to the dissolution of the domal salt stock by fresh water.

An anomalous salinity distribution was found in deeper deposits approximately 2.4 km (1.5 mi) south of Vacherie Dome. The total dissolved-solids content of water from the Nacatoch Formation was found to be approximately 1.7 times greater than water from the underlying Austin Group. Sufficient data are lacking to explain this anomaly.

The chemical character of the ground water in the East Texas Study Area also changes with increasing depth. Ground water in

shallow surficial aquifers is mostly calcium bicarbonate water. Predominant ions in the water change from calcium bicarbonate to sodium bicarbonate to sodium chloride with depth. Depth to saline water is shallowest over the domes, but generally coincides with the base of the Wilcox Group. Depth to saline water is greatest in the eastern and southeastern portions of the study area.

In the vicinity of Oakwood Dome, the chemistry of ground water appears to be similar to that found regionally. Generally, the water is a calcium bicarbonate or sodium bicarbonate type low in total dissolved solids. However, ground-water chemistry data available for this area are questionable on the basis of chemical balance checks. Additional data are needed to determine the chemistry of ground water in the vicinity of Oakwood Dome.

4.3.1.3 Water and Rock Interaction: Ground-water chemistry changes with depth in the ground-water reservoir of each study area. The sequence of change, reflected by the dominant ions in solution, is calcium bicarbonate to sodium bicarbonate to sodium chloride. Coinciding with this change is an increase in dissolved solids and pH.

The changes in ground-water chemistry with depth reflect chemical interaction between ground water and ground-water reservoir materials. As waters from the surface infiltrate to the ground-water reservoir, carbonic acid is depleted by dissolution reactions with reservoir materials and dissociation to bicarbonate, resulting in an increase in pH. Dissolved solids increase

with depth as dissolution of reservoir materials adds ions to solution. Calcium and magnesium are exchanged for sodium, occupying exchange sites on reservoir materials, resulting in a change from calcium bicarbonate water to sodium bicarbonate water with increasing depth.

At depths generally below the elevation of the base of fresh water, sodium and chloride are the dominant ions in solution. The concentration of these ions and total dissolved solids may be several times the concentration found in sea water. Several factors probably contribute to these increases. With increasing depth, flow rates of ground water tend to be slower. The longer contact time between water and rock, due to the slower rates of flow, may result in increased dissolution which increases the dissolved-solids concentration. Chloride concentration will tend to increase faster than other constituents' concentrations because it does not enter into many reactions which would remove it from solution. Processes of membrane filtration, the presence of trapped saline formation water, and the dissolution of evaporite deposits may also contribute to the composition of ground water in the study areas at depths below the base of fresh water.

4.3.2 RADIONUCLIDE RETARDATION: Movement of radionuclides in the ground-water reservoir will be affected by the advective and dispersive transport properties of the flow regime, chemical reactions between radionuclides and water and rock, and sorption and radioactive decay of radionuclides. These properties of the ground-water reservoirs need to be evaluated.

4.4 GEOLOGIC CHARACTERISTICS

A stratigraphy characterization was undertaken, and host rock/stress phenomena and rock strength/development, operation, and closure were investigated to enable comparison of geologic characteristics in each study area and at each dome.

4.4.1 STRATIGRAPHY CHARACTERIZATION: Depositional patterns in the northern portion of the Gulf Coastal Province reflect periods of inundation by shallow, quiet seas. These patterns are characterized by limestone and occasional evaporite deposition, alternating with regressive marine conditions, periods of erosion in the area far to the north, and associated Gulfward extension of deltas. The cyclic deposition has sufficient geographic extent for the resulting stratigraphic units to be mapped on the surface and in the subsurface throughout the region of the study areas.

4.4.1.1 Stratigraphy of the Study Areas: The stratigraphy of the East Texas Study Area consists of a succession of depositional sequences, each sequence consisting of a lower, dominantly fluvio-deltaic unit of sandstones and shales overlain by shelf carbonates and shales. An accumulation of up to 7,620 meters (25,000 ft) of sediments was deposited during six depositional intervals, beginning with the Louann Salt Sequence and terminating with the Wilcox-Claiborne Clastics (partial) Sequence. The sources of most of the detrital sediments were the topographically positive areas lying to the west and the north of the East

Texas Salt Basin. (See Table 4-5 for a lithologic description of the Upper Cretaceous and Tertiary sediments.)

The depositional history of the North Louisiana Study Area also consists of a series of depositional cycles, from the Late Triassic Eagle Mills through the Eocene Claiborne. Nearly 6,096 meters (20,000 ft) of sediments make up this stratigraphic section. The Monroe Uplift and the Sabine Uplift (see Figure 4-1) were important sources of sediment during the Cretaceous, but the major, long-term clastic sources were the Appalachian Mountains and high areas to the north drained by the Mississippi River, as well as streams draining southwestward from the Appalachian System. Cretaceous depositional cycles were somewhat masked by a high rate of clastic influx and by the realignment of structural features, caused by the rise of the Monroe and Sabine Uplifts and the subsidence of the Mississippi Embayment. (See Table 4-5 for a lithologic description of the Upper Cretaceous and Tertiary sediments.)

The stratigraphic section of the Mississippi Study Area consists of sedimentary sequences representing a cyclic history of marine transgressions and regressions over the Louann Salt. The section is up to approximately 8,230 meters (27,000 ft) thick in the southeastern portion of the study area, the result of massive sediment accumulations in the Mississippi Salt Basin (see Figure 4-1) largely during Jurassic and Cretaceous times. Sources of sediment for the various units within the study area ranged from reworked sediments of nearby older depositional sequences to

sediments brought in by major river systems from distant, uplifted regions to the north. (See Table 4-5 for a lithologic description of the Tertiary sediments).

4.4.1.2 Stratigraphy Near the Domes: The Cretaceous and Tertiary sediments surrounding each dome are similar, consisting of marine and nonmarine, unconsolidated sands, silts, clays, chalks, and marls. Many stratigraphic units become thinner over the domes or are absent because of nondeposition or erosion resulting from domal growth.

The ages of the outcropping beds at Oakwood Dome range from Tertiary (Eocene) to Quaternary (Pleistocene and Recent). The Eocene outcrop consists of rocks of the lower to middle Claiborne Group. The Quaternary, Pleistocene, and Recent deposits display alluvial terrace sediments and alluvium.

The subsurface geologic section around Oakwood Dome has beds of the Late Triassic Series, the Jurassic Series, the Comanchean and Gulfian Series, and the Paleocene and Eocene Series. Thinning of sediments over the dome indicate that domal movement continued through deposition of the Claiborne Group.

The beds exposed at Keechi Dome include those of the Upper Cretaceous, Tertiary, and Quaternary. The Upper Cretaceous beds consist of the Taylor and Navarro Groups of the Gulfian Series; the Tertiary beds consist of the Midway, Wilcox, and lower Claiborne Groups; the Quaternary sediments consist of Pleistocene terrace deposits and Recent floodplain deposits.

The subsurface geologic section around Keechi Dome is similar to that around Oakwood Dome. Some thinning of Tertiary units is evident over the dome, indicating sedimentation during salt movement.

The beds exposed at Vacherie Dome include those of Tertiary and Quaternary ages. The Tertiary sediments consist of the upper Paleocene-lower Eocene Wilcox Group and the lower part of the Eocene Claiborne Group. The Quaternary sediments consist of Pleistocene terrace deposits and Recent alluvium.

The subsurface geologic section around Vacherie Dome contains Jurassic, Upper and Lower Cretaceous, and Tertiary sediments. Limited lithologic information is available for subsurface units at Vacherie, particularly those of Jurassic and Early Cretaceous ages. Thinning of Upper Cretaceous and lower Tertiary (Midway and Wilcox Groups) beds over the dome indicate deposition during salt movement at least through the early Eocene.

The beds at Rayburn's Dome include those of Upper Cretaceous, Tertiary, and Quaternary ages. The Upper Cretaceous outcrop has been interpreted, on the basis of paleontologic data, to be part of the Navarro Group. The Tertiary, Paleocene and Eocene beds belong to the Midway, Wilcox, and Claiborne Groups. The Quaternary sediments consist of Pleistocene terrace deposits and Recent alluvium.

The subsurface geologic section around Rayburn's Dome is similar to that around Vacherie Dome. Only Quaternary sediments occur on top of the dome. Tertiary beds thin and crop out on the flanks of the dome, indicating salt movement through the Eocene.

The geologic units exposed in the Cypress Creek near-dome area include those of Tertiary and Quaternary ages. The Tertiary sediments consist of the Hattiesburg Formation and probably part of the Citronelle Formation. The Quaternary sediments consist of the Citronelle Formation and alluvium. The Hattiesburg is exposed over approximately one-third of the near-dome area. The Citronelle, which caps all of the hills in the area, is found over the remainder of the near-dome area not occupied by Recent alluvium of the floodplains of Cypress Creek and its major tributaries.

The subsurface stratigraphic section in the Cypress Creek Dome area includes Paleocene and younger strata. Sediments of the Midway, Wilcox, Claiborne, Jackson, and Vicksburg Groups surround the dome, but only deposits of Miocene age and younger occur on top of the dome.

Precise information on the lithology and distribution of the stratigraphic units exposed over Lampton Dome is not available due to the lack of access to many areas during the Area Characterization field program. However, the Geologic Map of Mississippi (Mississippi Geological Survey, 1969) indicates that Tertiary, Pascagoula-Hattiesburg beds are exposed over the major portion of the near-dome area. The Geologic Map of Mississippi also indicates that Quaternary Citronelle deposits are found in the near-dome area. Recent alluvium is undoubtedly present in the floodplains of the larger streams.

The subsurface stratigraphic section investigated in the Lampton Dome area includes all beds younger than the Upper

Cretaceous Selma Group. Sediments of the Midway, Wilcox, Claiborne, Jackson, and Vicksburg Groups surround the dome, but apparently only deposits of Miocene age and younger occur on top of the dome.

The stratigraphic units exposed in the Richton Dome area include those of Tertiary and Quaternary ages. The Tertiary sediments consist of the Hattiesburg Formation and the lower part of the Citronelle Formation. The Quaternary deposits consist of the upper part of the Citronelle Formation, terrace deposits, and alluvium. The Hattiesburg beds are exposed principally on the interstream divides at the higher topographic levels and in the drainage courses where terrace and Recent alluvial deposits are absent. The Citronelle covers more than 20 percent of the near-dome area and is exposed on the higher interstream hills. Terrace deposits are found at several topographic levels in the valleys of several creeks adjacent to and over the dome. Recent alluvium fills the modern valleys and underlies the floodplains of Bogue Homo and Thompson Creeks and the lower portion of Beaver Dam Creek.

The subsurface stratigraphic section studied in the Richton Dome area includes all strata younger than the Upper Cretaceous Selma Group. Sediments of the Midway, Wilcox, Claiborne, Jackson, and Vicksburg Groups surround the dome, but only deposits of Miocene age and younger occur on top of the dome.

4.4.2 HOST ROCK/STRESS PHENOMENA: The caprock and salt stock at five domes, Cypress Creek, Richton, Vacherie, Rayburn's, and Oakwood, were cored during Area Characterization.

The core hole at Oakwood Dome penetrated 137 meters (450 ft) of caprock and 59 meters (193 ft) of salt stock. The caprock is divided into a lower anhydrite section, a narrow transition zone, and an upper calcite section. The contacts between the caprock and the underlying salt, and the caprock and the overlying Wilcox sandstone are sharp and tight. Salt core data indicate that the salt is 90 to 95 percent pure halite, with anhydrite and traces of calcite as impurities (Kreitler, 1980). The halite crystals are elongate and are 25 to 76 mm (1 to 3 in) in length. The anhydrite occurs in stringers, and no evidence of shear zones within the salt core have been noted.

Other analyses at this site include strain analyses at eight points along the core. Results indicated that the "...mean percentage shortening parallel to Z (the principal axis of shortening) decreases significantly from 50 (depth 408.1 meters (1,339 ft)) to 39 (depth 359.0 meters (1,178 ft)). The mean shortening further declines to 15 percent in the recrystallized upper 2 meters (7 ft) of "unfoliated" rock salt (depth 355.4 meters (1,166 ft)). This upward decrease in strain is compatible with petrographic observations on the core...The present fabrics represent...repeated episodes of strain and recrystallization during diapirism...In the recrystallized rock salt just below the caprock, (strain values suggest)...that some time after recrystallization this zone was subjected to weak uniaxial compression

along a subvertical axis. The most likely agent for this compression is an upward-directed force from the rising diapir, which may have contributed to the tight seal of the caprock contact where drilled" (Jackson, 1980).

The core hole at Vacherie Dome penetrated 83 meters (273 ft) of caprock and 1,289 meters (4,228 ft) of salt stock. The caprock is divided into a lower anhydrite zone 76 meters (249 ft) thick, a middle gypsum section 1 meter (3 ft) thick, and an upper carbonate zone 6 meters (21 ft) thick. The contact between the anhydrite zone and the salt is sharp, horizontal, and tightly cemented. Salt core data indicated that the salt consists of approximately 90 percent halite and 10 percent anhydrite. The beds of relatively pure halite are thin; the anhydrite and salt layers are highly contorted, nonparallel, and discontinuous, often isoclinally folded over distances of 0.3 to 0.6 meter (1 to 2 ft). Halite crystals in the core are typically 6 to 25 mm (0.25 to 1.0 in) in diameter and elongated parallel to layering (Nance, Rovik and Wilcox, 1979).

The core hole at Rayburn's Dome penetrated 9 meters (30 ft) of caprock (only 1 meter (3.5 ft) was recovered), and 1,486 meters (4,875 ft) of salt stock. The interval of caprock recovered consists of an upper limestone zone containing solution cavities and angular rock fragments, and a lower zone containing anhydrite with gypsum bands. The nature of the caprock-salt interface is not known because the section of core containing the contact was not recovered. Salt core data indicated that the salt consists of approximately 95 percent halite and 5 percent

anhydrite. The halite and anhydrite layers are uncontorted and subparallel. Halite crystals in the core are generally 6 to 25 mm (0.25 to 1.0 in) in diameter above a depth of 335 meters (1,100 ft) and are greater than 51 mm (2.0 in) in diameter below that depth. Some isolated crystals are as long as 457 mm (18 in) (Nance and Wilcox, 1979).

The core hole at Cypress Creek Dome penetrated 62 meters (204 ft) of caprock and 156 meters (513 ft) of salt stock. The caprock core from Cypress Creek Dome consists predominantly of anhydrite and gypsum. Fine-grain gypsum appears to have replaced the anhydrite in zones in the upper part of the caprock. The lower portion of the caprock core contains approximately 80 percent anhydrite, with the remainder consisting of gypsum in veins and small blebs. Near the caprock-salt contact, gypsum veins are absent and the anhydrite grades into granular halite. The salt core generally contains less than 10 percent anhydrite, with discrete bands that are up to 25 percent anhydrite. The salt consists of fine- to coarse-grain, equidimensional or prolate halite crystals with anhydrite bands and xenoliths present throughout (Drumheller, Cavan, and Fuerst, 1981).

The core hole at Richton Dome penetrated 65 meters (213 ft) of caprock and 155 meters (508 ft) of salt stock. The caprock consists of anhydrite with gypsum-filled veins, except in the upper 7 meters (23 ft), where vuggy limestone was interbedded with calcite. Several brecciated, vuggy, gypsum-rich zones with minor quantities (less than 2 percent) of native sulphur and calcite occur in the lower part of the caprock. Salt core data

indicate that the salt is composed of approximately 90 percent halite and 10 percent anhydrite. The halite crystals are generally fine- to coarse-grained (less than 51 mm (2 in) in diameter) and equidimensional to prolate. Numerous halite megacrystal zones, which are usually bordered by an anhydrite band approximately 6 mm (0.25 in) thick, are present (Drumheller, Fuerst, Cavan, and Saunders, 1981).

Stress phenomena of the salt stocks will be addressed during Location and Site Characterization.

4.4.3 ROCK STRENGTH/DEVELOPMENT, OPERATION, AND CLOSURE:

Borehole closure was monitored at Vacherie Dome, using caliper logs that were run at different time intervals after completion of the core hole (Thoms and Mogharrebi, 1979). The core hole suffered a 17 percent loss of volume during the first 3 months after its completion. Two months later, a caliper log was again run, and the closure had apparently stabilized or ceased.

The Rayburn's core hole was also monitored for closure, but none was detected. In fact, the borehole may have even enlarged, possibly due to undersaturation of the brine that was left in the hole. Four months after its completion, it was still apparently stable.

No core holes in Mississippi or Texas were monitored for closure.

The strength of the salt, caprock, and overburden will be evaluated thoroughly during Location and Site Characterization.

4.5 TECTONIC ENVIRONMENT

Tectonic elements, Quaternary faults, Quaternary igneous activity, uplift and subsidence, and seismicity were investigated to enable comparison of the tectonic environment in each study area and at each dome.

4.5.1 TECTONIC ELEMENT EVALUATION: Regional faulting in the study areas is generally associated with salt movement. The Hosston Fault System is the nearest major regional fault zone to Vacherie and Rayburn's Domes. This system lies 80 and 113 km (50 and 70 mi), respectively, to the northwest. Nearest to Richton, Cypress Creek, and Lampton Domes is the Pickens-Quitman-Gilbertown-Pollard Fault Zone, which lies 72, 90, and 121 km (45, 56, and 75 mi), respectively, to the northeast of the domes. The Mt. Enterprise Fault System is the nearest regional fault to the two Texas candidate domes. It lies 24 km (15 mi) southeast of Oakwood Dome, and 23 km (14 mi) southeast of Keechi Dome. Table 4-9 summarizes the distance from each dome to the nearest major regional fault.

Regional gravity data show linear anomalies along the Mt. Enterprise Fault System in east Texas that could indicate faulting, irregularities in the basement, or appreciable changes in the depositional dip. Additional data are needed to adequately substantiate faulting of the pre-salt basement.

TABLE 4-9. DISTANCE FROM DOMES TO REGIONAL FAULTS

Dome	Distance to Nearest Major Regional Fault (miles)*
Oakwood	15
Keechi	14
Vacherie	50
Rayburns	70
Lampton	75
Richton	45
Cypress Creek	56

*To convert to kilometers, multiply by 1.609.

4.5.2 QUATERNARY FAULTS: Faults associated with salt movement generally became inactive during Tertiary time. However, the Texas Bureau of Economic Geology has concluded that there may have been Quaternary age faulting 24 km (15 mi) northeast of Oakwood Dome and 23 km (14 mi) south of Keechi Dome associated with salt movement (Collins and Hobday, 1980). This faulting occurs along the surface projection of the subsurface western extension of the Mt. Enterprise Fault Zone and is in proximity to the Trinity River.

Overdome and near-dome faults related to dome development appear to be present at all the domes for which there is enough data to allow detection. There is, however, no evidence of faulting of the Quaternary deposits over the domes, suggesting a pre-Quaternary age for the dome-related faulting.

4.5.3 QUATERNARY IGNEOUS ACTIVITY: There is no indication of any Quaternary igneous activity in the study areas or the Gulf Interior Region.

4.5.4 UPLIFT/SUBSIDENCE: Geomorphic evidence indicates that the Gulf Interior Region has been stable for at least the past several million years. The Gulf Interior Region is currently experiencing an erosion cycle.

The thinning of the stratigraphic section over Oakwood Dome, from lower Taylor through Claiborne time, suggests that domal movement continued through Claiborne deposition. The absence of faulting or warping of the Quaternary terrace deposits indicates that there has been no post-Quaternary uplift. However, the Texas Bureau of Economic Geology has reported that alluvial deposits directly over the crest of the dome are thicker than those off the dome flanks, and has interpreted this as an indication of possible collapse in the caprock or salt, or retreat of the salt stock.

Some thinning of Tertiary sediments occurs over Keechi Dome with beds of the Claiborne Group showing less thinning than those of the Wilcox. This observation suggests decreased domal growth during the late Eocene. Faulting, warping, or thickening of Quaternary terrace deposits has not been observed over the dome, indicating that there has been no Quaternary or post-Quaternary uplift or subsidence.

Faults and down-dropped fault blocks in the Tertiary and Cretaceous sediments over Vacherie Dome indicate uplift and

possible salt dissolution and subsidence during the Tertiary. Thickening of Quaternary deposits over the western part of the dome suggests that subsidence may have occurred in that area during the Quaternary. Arcuate lineaments in Quaternary deposits east of Vacherie Dome may also indicate domal movement during the Quaternary, but the relation of these lineaments to domal movement is speculative.

Upwarped Wilcox and Claiborne Group beds at Rayburn's Dome indicate domal movement as late as the Eocene. Quaternary deposits are thicker on the eastern, northern, and western sides of the topographic depression over the dome and thinnest over the central part of the dome. These observations suggest that the outer edges of the salt dome may have collapsed due to salt dissolution during the Quaternary. Faulting of the Quaternary deposits has not been detected.

Analyses of the structure of the surficial units at Cypress Creek Dome indicate that subsidence has taken place during the Quaternary. A closed depression exists on the Hattiesburg-Citronelle contact over the dome. The area above this depression is filled with an anomalously thick section of Quaternary alluvium. In addition, a reduction-oxidation sequence in the Quaternary alluvium suggests infilling of a subsiding area and temporary, cyclical impoundment of drainage.

There is no known evidence at Lampton Dome to suggest uplift or subsidence during the Quaternary. Surface elevations above the dome are typical of the interstream topography in the area, suggesting that domal movement has not controlled the drainage courses or topographic development.

Structural analyses of the surficial units at Richton Dome indicate domal movement may have occurred as late as the Miocene, as evidenced by the presence of faulting in Hattiesburg strata. However, there is no clear evidence that domal growth or salt dissolution and subsidence has exerted influence or control on the geomorphic features in the area during the Quaternary.

4.5.5 SEISMICITY/GROUND MOTION/CREDIBLE EARTHQUAKE: There is no known correlation between structural areas and earthquake epicenters within the Gulf Interior Region. Therefore, on the basis of accepted methods of seismic risk analysis, the Gulf Interior Region, including all of the dome areas, is considered tectonically stable and subject only to earthquakes of low intensity (maximum of VI on the Modified Mercalli scale).

The maximum expected peak horizontal surface acceleration for any of the candidate domes is 0.06g. This acceleration can occur at the domes due either to a local earthquake event of intensity VI MM at a dome, or to an earthquake event of intensity VII MM which occurs to the north in the Ouachita or Wichita-Arbuckle seismo-tectonic regions (see Figure 4-1) and which is propagated to the dome areas.

Subsurface accelerations at depths of 610 to 914 meters (2,000 to 3,000 ft) are calculated to be about one-third of the surface accelerations.

4.6 HUMAN RESOURCES

Mineral resource potential, exploration history/use, and land ownership/access were investigated to enable comparison of the potential for human resources at each dome.

4.6.1 RESOURCES: The following types of potential resources were evaluated: asphaltic rock, bentonite and other volcanic materials, brines and salt, cement materials, construction and road materials, geopressured and geothermal resources, heavy minerals, iron ore, lignite, oil, natural gas, and unusual gases.

Petroleum and lignite are the significant mineral resources in the Oakwood Dome area. Petroleum exploration and development at Oakwood has been continuing since the discovery of Oakwood Dome Oil Field in 1958. Production to date has generally been limited to the eastern half of the dome, where wells produce from beneath the salt overhang. There has been a decline in production since 1963. Future petroleum potential in the near-dome area is quite low. Large thicknesses of lignite have been reported in wells at Oakwood Dome; but as of this date, field borings have not supported or disclaimed the reports. Future development depends on the substantiation of a minimum commercial thickness of lignite or the development of production-type gasification systems. Although numerous other mineral resources are present at Oakwood, they are rated as nonproductive, nonexploitable, nonusable, or negligible to speculative.

There is no significant mineral resource extraction currently operating at Keechi Dome; however, there is minor

potential for future development of both petroleum and lignite. Petroleum exploration began in the early 1900's and has continued sporadically. Although exploration drilling in the domal area has reported some "good shows", no commercial production has been developed. Potential exists for asphaltic sands to be found at Keechi near the surface in the Queen City Formation and at depth in the Woodbine Formation. Resource development of these sands, if mineable, would probably be limited to a local market. The potential lignite resources at Keechi Dome are in the upper portion of the Wilcox Group. Future development will be dependent on areal continuity and thickness of the seams as well as on the applicability of onsite gasification equipment. Other mineral resources present at Keechi Dome are rated nonproductive, nonexploitable, nonusable, or negligible to speculative.

Potential mineral resources at Vacherie Dome include sand, ground water, gravel, salt, gypsum, anhydrite, lignite, oil, and gas. However, the availability of more abundant, shallower and more profitable sand, gravel, salt, gypsum, anhydrite, and lignite deposits elsewhere in the Gulf Coast Region precludes the development of important operations at Vacherie. All but the northwest flank of Vacherie Dome have been drilled since the early 1920's without oil or gas production. The probability of finding substantial quantities of oil or gas is low.

Potential mineral resources at Rayburn's Dome include sand, gravel, salt, gypsum, anhydrite, limestone, lignite, agricultural lime, oil, and gas. The potential for developing sand, gravel, salt, gypsum, anhydrite, and limestone is good due to the shallow

depth of the dome; however, a high saline water table would hamper any deep surface mining operation. The economic importance of lignitic deposits at Rayburn's is unevaluated. Thicker, shallower, lignitic seams of known grade are present elsewhere in northern Louisiana. Agricultural lime was quarried at Rayburn's Dome in the 1940's, but the low quality of the lime and the limited areal extent of the source rock will probably preclude future quarrying. Six wells have been drilled on the flanks of Rayburn's Dome with no resulting oil or gas production. The probability of finding economically productive reservoirs is considered low.

Proven mineral resources in the Cypress Creek Dome area consist solely of hydrocarbons. Past production of sand and gravel is inferred from the presence of gravel pit symbols on topographic maps of the area. However, field examinations revealed no recent use of sand, gravel, or clay, nor did they disclose the occurrence of any deposits of these minerals which might be commercial. A small oil and gas field is located on the flanks of Cypress Creek Dome. Although the dome is situated along the extension of a productive trend, evaluation of available information indicates that the near-dome area has a poor to fair potential for future hydrocarbon production. No other mineral resources are considered to have a commercial potential in the context of current economics and marketability.

Proven mineral resources in the Lampton Dome area are limited to minor gravel production from open pits. Clay is present in potentially commercial quantities but is not currently being

produced in the near-dome area. No oil or gas production has been developed in the immediate vicinity of the dome nor in nearby areas. While all strata older than Miocene may optimistically be considered potentially prospective, oil and gas potential at Lampton Dome is considered speculative to poor. However, extensive faulting on the southeastern flank of Lampton Dome may yet prove to be a trap for petroleum accumulation. Lampton Dome has undergone extensive sulfur exploration. However, no sulfur production has been established at this dome, nor at any other dome in the three interior basins. No other mineral resources are considered to have an encouraging commercial potential in the context of current economics and marketability.

Proven mineral resources in the Richton Dome area are limited to sand and gravel. Due to the abundance of these materials in the region, sand and gravel have low potential for development except for local use. Clay is present near the dome in potentially usable quantities. The quality of the clay is not known and clay has not been produced yet in the dome area. Several petroleum exploration wells have been drilled and abandoned in the area with no production being reported. The potential for discovery of additional petroleum resources in the vicinity of Richton Dome is rated as being speculative to highly speculative. Sulfur test wells have been drilled into the Richton Dome caprock with no reported production. The possibility of development of hydrogen sulfide gas and sulfur from the caprock is rated as speculative. No other mineral resources are considered to have an encouraging commercial potential in the context of current economics and marketability.

The economic practicality of attempting to exploit the known resources of the candidate domes is low in comparison with other known deposits. Higher-quality resources exist in other parts of the country in much greater quantities than in the area of the domes. Development of any of the resources around the domes would be of low priority.

4.6.2 EXPLORATION HISTORY/USE: The exploration history in the vicinity of each of the seven candidate domes was investigated and all known exploration borings within a 8-km (5-mi) radius at each dome were identified. The number of exploration borings at each dome is summarized in Table 4-10.

TABLE 4-10.
EXPLORATION HISTORY AT THE DOMES

Dome	Number of Borings Within -914-meter (-3,000-ft) MSL Salt Contour		Total Borings Within 8-km (5-mi) Radius of Dome Center
	Penetrating Salt	Penetrating Caprock	
Oakwood	35	36	74
Keechi	8	8	88
Vacherie	9	10	168
Rayburns	3	23	66
Cypress Creek	6	6	13
Lampton	1	8	20
Richton	9	31	49

Twenty-two of the exploratory borings that penetrated salt at Oakwood Dome were sidetracked, producing a total of 84 holes into the sediments below the overhang. Twenty-four of these wells have produced oil or gas.

Five petroleum exploration wells have been drilled through the salt overhang at Cypress Creek. Three of these wells are actively producing oil and gas.

4.6.3 LAND OWNERSHIP/ACCESS: Land ownership in the vicinity of Oakwood Dome is predominantly private. Within a 3-km (2-mi) radius of the dome center there are about 30 property owners, one of which controls about 60 percent of the area.

Land in the vicinity of Keechi Dome is privately owned. There are approximately 25 separate land owners within a 3-km (2-mi) radius of the center of the dome.

Land over Vacherie Dome is predominantly privately owned. Willamette Industries owns approximately 227 hectares (560 acres) at the eastern end of the dome, as well as several large tracts elsewhere in the surrounding area.

The major portion of the land area above Rayburn's Dome and in the dome vicinity is either owned in fee or leased by Continental Forest Industries. The rest of the land in the area is privately owned. Individual tracts vary in size from about 16 to 65 hectares (40 to 160 acres).

The Cypress Creek near-dome area is located within a national forest, which includes a military training facility. Approximately 90 percent of the near-dome area is utilized for commercial

forestry. The remainder consists of isolated parcels of privately owned land, except for a 2.6 km^2 (1 mi^2) overlying the dome, which is owned by Perry County.

Approximately 85 percent of the Lampton near-dome area is privately owned. The remainder of the area is within a state-owned game reserve.

Land in the Richton near-dome area is privately owned, principally by the Masonite Corporation. Section 16 in each township in the area is owned by Perry County. A small amount of acreage is owned by the town of Richton.

4.7 SURFACE CHARACTERISTICS

Area and near-dome surface hydrology studies were conducted during Area Characterization. The surface hydrologic setting was described in each of the study areas and the regional relationships between base flow of streams and surface geology were identified. Topography, drainage, and flooding potential in the vicinity of the candidate domes were also investigated.

4.7.1 REGIONAL SURFACE-WATER HYDROLOGY: The Mississippi Study Area is located within the two major watersheds of southeastern Mississippi, those of the Pascagoula River and the Pearl River. The Leaf River and Black Creek, which drain most of the study area, are tributaries of the Pascagoula River. Cypress Creek and Richton Domes are in the Pascagoula River watershed, and Lampton Dome is in the Pearl River watershed (Figure 4-16).

89°45'
89°30'
89°15'
89°00'
88°45'
31°30'
31°15'
31°00'

JEFFERSON DAVIS
COVINGTON
JONES
WAYNE
MARION
LAMAR
FORREST
PERRY
GREENE
WALTHALL
PEARL RIVER

BASSFIELD
SUMRALL
HATTIESBURG
COLUMBIA
LAKE BILL WALLER
LAMPTON DOME
PURVIS
NEW AUGUSTA
RICHTON
RICHTON DOME
CYPRESS CREEK DOME
LUMBERTON
STUDY AREA

BOWIE CREEK
LEAF RIVER
BLACK CREEK
TALLAHALA CREEK
HOMO CREEK
BOGUE HOMO
THOMPSON CREEK
PINE BOX CREEK
CHEHAWAY RIVER
PEARL RIVER
UPPER LITTLE RIVER
LOWER ELBOW CREEK
LITTLE CREEK
CYPRESS CREEK
LEAF RIVER
MISSISSIPPI

STUDY AREA OUTLINE

N

5 0 5 MILES
8 4 0 8 KILOMETERS

LEGEND

SALT DOME SHOWING LOCATION OF -3000 FEET MEAN SEA LEVEL CONTOUR ON SURFACE OF SALT

PREPARED	LHH	DATE	9/28/81
REVISED	DAP	DATE	11/25/81
REVISED		DATE	
APPROVED	RSM	DATE	9/28/81

T-1928-1

NATIONAL WASTE TERMINAL STORAGE PROGRAM
GEOLOGIC EVALUATION GULF COAST SALT DOMES
LAW ENGINEERING TESTING COMPANY
MARIETTA, GEORGIA

MISSISSIPPI STUDY AREA
REGIONAL DRAINAGE

JOB NO. MV9600 FIGURE 4-16

BEST DOCUMENT AVAILABLE

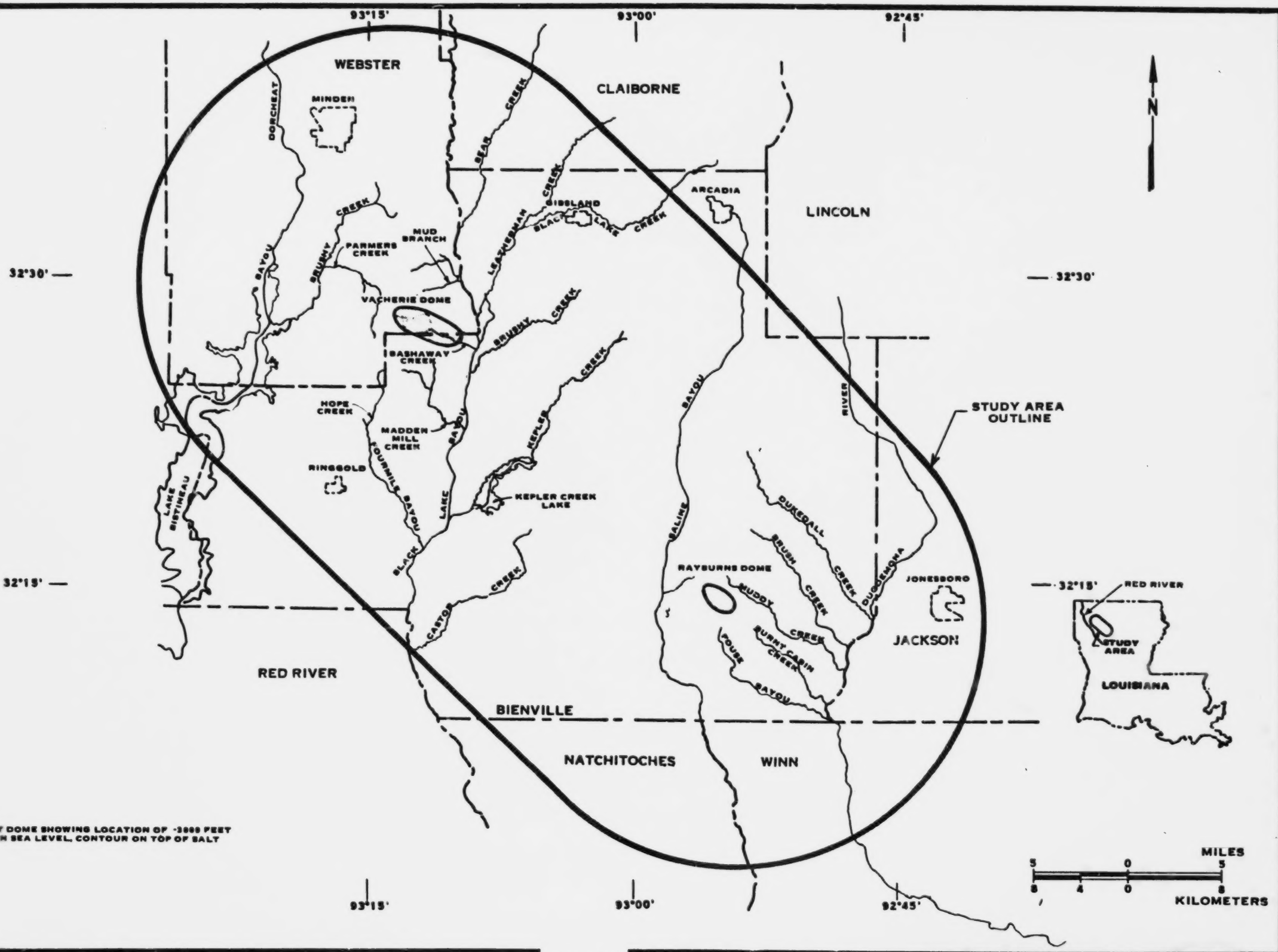
The 7-day, 2-year low flow of streams generally decreases to the east and north across the Mississippi Study Area. Ground-water discharge to streams is greatest in areas of permeable sand and gravel deposits of the Citronelle Formation in the western portion of the study area. Recharge is high, surface runoff is low, and ground-water storage is large in these areas. Ground-water discharge is less in other areas where the relatively less permeable Hattiesburg Formation is the dominant surficial unit.

The North Louisiana Study Area is in the southeastern portion of the Red River watershed, the southernmost of the main tributaries of the Mississippi River. Bayou Dorcheat, Black Lake Bayou, Saline Bayou, and the Dugdemona River drain the study area (Figure 4-17). These streams are tributaries to the Red River. Vacherie Dome is located in the Black Lake Bayou watershed and Rayburn's Dome is located in the Dugdemona River watershed.

The 7-day, 2-year low flow of streams in the North Louisiana Study Area generally increases to the south and east. Ground-water discharge is into major streams from near-surface deposits.

The East Texas Study Area is located mostly within the Trinity River watershed (Figure 4-18). Palestine and Keechi Domes are located in the Keechie Creek watershed, and Oakwood Dome is located in the Upper Keechi Creek watershed. Keechie Creek and Upper Keechi Creek are minor tributaries of the Trinity River.

Discharge occurs to major streams in the East Texas Study Area from formations incised by these streams. This ground-water



NORTH LOUISISANA STUDY AREA
REGIONAL DRAINAGE

JOB NO. MV9600

FIGURE 4-17

NATIONAL WASTE TERMINAL STORAGE PROGRAM
GEOLOGIC EVALUATION GULF COAST SALT DOMES

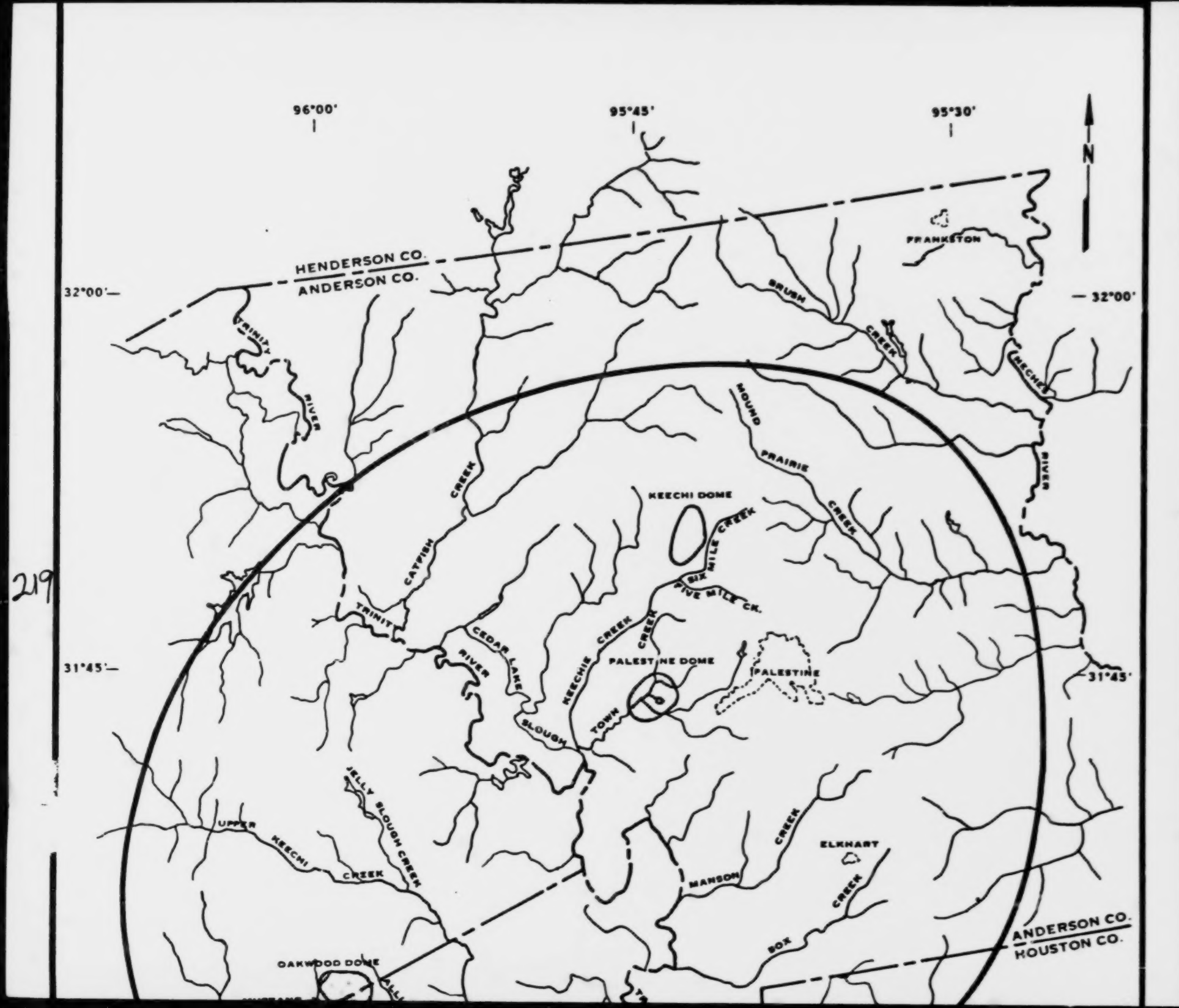
LAW ENGINEERING TESTING COMPANY MARIETTA, GEORGIA

PREPARED	RSM	DATE 3/1/80
REVISED	RSM	DATE 11/26/80
REVISED	DLP	DATE 1/30/81
APPROVED	GHE	DATE 2/16/81

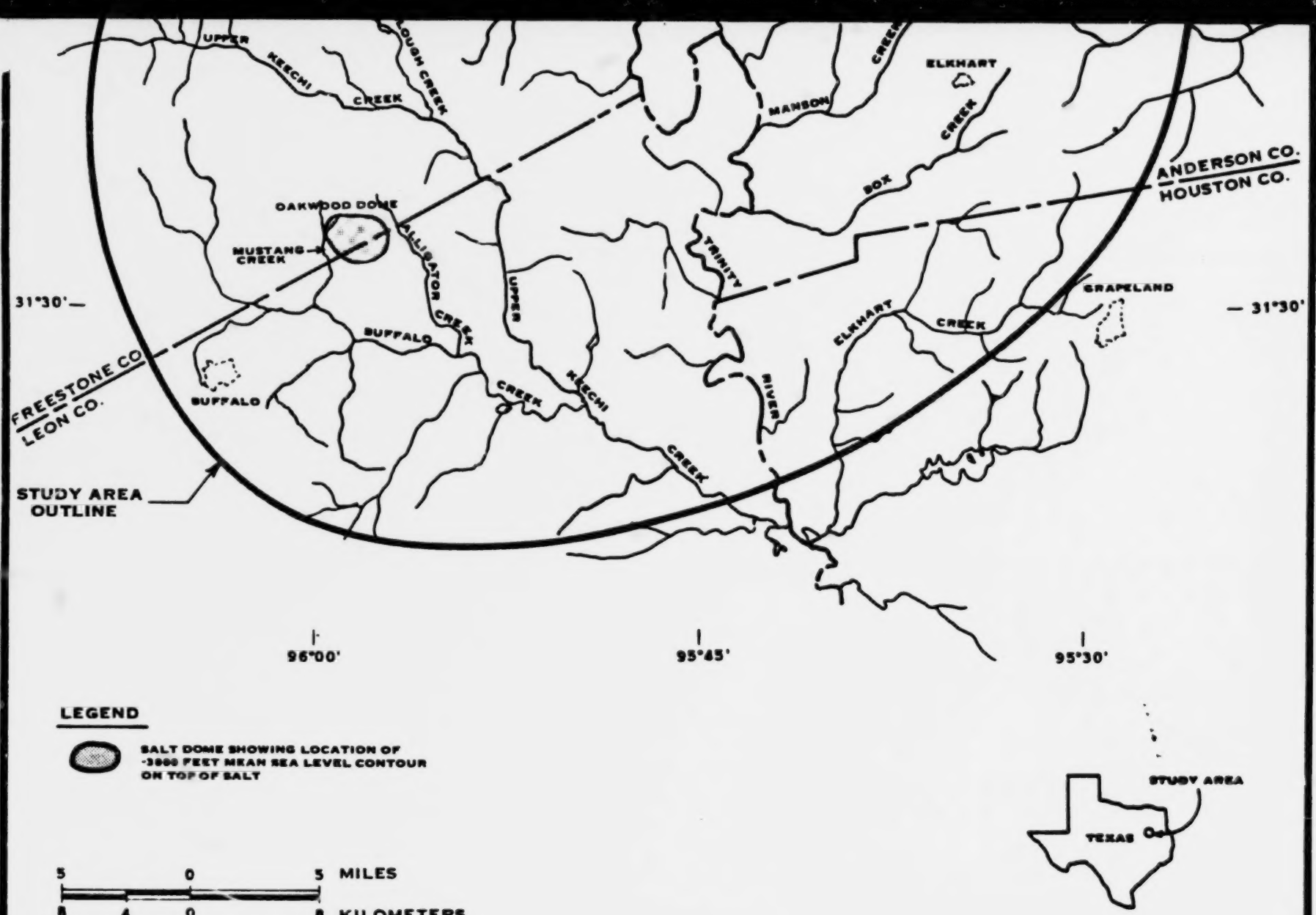
T-1929-1

BEST DOCUMENT AVAILABLE

FIGURE 4-17


96°00'
95°45'
95°30'
N
HENDERSON CO.
ANDERSON CO.
32°00'
32°00'
FRANKSTON
BRUSH CREEK
KECHI CREEK
TRINITY RIVER
MOUND PRAIRIE CREEK
RIVER
CATFISH CREEK
KEECHI DOME
SIX MILE CREEK
FIVE MILE CK.
TRINITY
CEDAR LAKE
KEECHIE CREEK
PALESTINE DOME
PALESTINE
31°45'
31°45'
SLOUGH
TOWN
JELLY SLOUGH CREEK
UPPER KEECHI CREEK
MANSON CREEK
ELKHART
BOX CREEK
OAKWOOD DOME
ANDERSON CO.
HOUSTON CO.

219



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APPROVED	[signature]	DATE	[illegible]

T-1930-1

NATIONAL WASTE TERMINAL STORAGE PROGRAM
GEOLOGIC EVALUATION GULF COAST SALT DOMES

LAW ENGINEERING TESTING COMPANY
MARIETTA, GEORGIA

EAST TEXAS STUDY AREA
REGIONAL DRAINAGE

JOB NO. MV9600 FIGURE 4-18

FIGURE 4-18

BEST DOCUMENT AVAILABLE

discharge is probably greatest in the northwestern part of the study area, decreasing to the south and east.

4.7.2 SURFACE-WATER HYDROLOGY AND TOPOGRAPHIC FEATURES OF THE CANDIDATE DOMES: Richton Dome is located along the drainage divide between the Bogue Homo and Thompson Creek watersheds (see Figure 4-16). The domal area is drained radially by several minor tributaries to these creeks. Both creeks are tributaries to the Leaf River.

The topography over Richton Dome is gently rolling to hilly with surface elevations varying from 87 meters (287 ft) MSL in the central area of the dome to 50 meters (164 ft) MSL along Pine Branch at the southeastern edge of the domal area.

Probable maximum flooding on streams crossing the Richton Dome area would inundate about 264 hectares (653 acres), or approximately 12 percent, of the area defined by the surface projection of the -610-meter (-2,000- ft) -MSL salt dome contour. The most significant flood potential over the dome is from Pine Branch, a tributary to Thompson Creek. Pine Branch watershed covers 11 km^2 (4.2 mi^2) and drains approximately 50 percent of the site area.

Base flow of streams in the vicinity of Richton Dome suggest that the average hydraulic properties of the surficial geologic unit in this area, the Hattiesburg Formation, are relatively low and that local recharge is minimal. The 7-day, 2-year low flow for both Thompson Creek and Bogue Homo in the vicinity of Richton Dome is approximately 0.85 l/sec (0.03 ft^3/sec) per square mile

drainage area (Shows and others, 1966). This value is low compared to those from streams in other portions of the Mississippi Study Area.

Cypress Creek Dome is located in the Cypress Creek watershed, a tributary to Black Creek, which flows into the Pascagoula River (see Figure 4-16). The domal area is drained by the headwaters of Cypress Creek.

The topography over Cypress Creek Dome is gently rolling to hilly with elevations at the dome varying from 55 meters (180 ft) MSL to 82 meters (270 ft) MSL.

The character of the drainage over the dome is inconsistent with the regional dendritic pattern. A drainage pattern which includes an upland swamp covers a depression in the central portion of the domal area.

Probable maximum flooding on streams crossing Cypress Creek Dome would inundate about 456 hectares (1,128 acres), or approximately 44 percent of the area defined by the surface projection of the -610-meter (-2,000- ft) -MSL salt dome contour.

Low flows of streams in the vicinity of Cypress Creek Dome suggest that the hydraulic properties of the surficial geologic unit, the Citronelle Formation, are relatively high and that local recharge to this formation is also high. The 7-day, 2-year low flow for Black Creek, 18 km (11 mi) upstream from its confluence with Cypress Creek, is approximately 6 l/sec (0.2 ft^3/sec) per square mile of drainage area (Taylor and others, 1968). This is the closest point to Cypress Creek for which data were available and is probably representative of dry-weather flows for Cypress Creek.

Figure 4-17). The watershed is characterized by gently rolling hills with a relatively wide alluviated floodplain. Surface elevations range from 50 to 120 meters (165 to 395 ft) MSL. The drainage pattern of Bashaway Creek is dendritic.

Probable maximum flooding on Bashaway Creek and its tributaries would inundate about 174 hectares (430 acres), or approximately 18 percent of the area defined by the surface projection of the -610-meter (-2,000- ft) -MSL salt dome contour.

In the vicinity of Vacherie Dome, water from both the alluvial deposits and the Sparta Formation contribute to the base flow of streams. The base flow of streams in the vicinity of the dome that derive water from the Sparta Formation suggests that the hydraulic properties of the Sparta Formation in this area are relatively high and that local recharge is good. The 7-day, 2-year low flow for Brushy Creek, near Liberty, Castor Creek, at Castor, and Kepler Creek, near Sparta, are, respectively, 0.28, 5 and 6 l/sec (0.01, 0.16, and 0.2 ft^3/sec) per square mile drainage area (Speer and others, 1966). This range of values is typical of other streams in the study area that derive their low flow from the Sparta Formation.

Rayburn's Dome is located along the drainage divide between Fouse Bayou and Muddy Creek watersheds (see Figure 4-17). Both streams are tributaries to the Dugdemona River, and their watersheds are characterized by gently rolling to hilly topography with relatively wide alluviated floodplains. Elevations in these watersheds range from 37 to 98 meters (120 to 320 ft) MSL. The drainage pattern of both streams is dendritic.

Lampton Dome is located along the drainage divide between Upper and Lower Little Creeks, two tributaries to the Pearl River (see Figure 4-16). The domal area is drained radially by several minor tributaries to Upper and Lower Little Creeks.

The topography overlying Lampton Dome is gently rolling to hilly with an east-west trending topographic divide separating the domal area into approximately two equal parts. Topography north of this divide is considerably more rugged than south of the divide. Elevations vary from 112 meters (367 ft) MSL near the center of the dome to 58 meters (190 ft) MSL at the northeast corner.

Probable maximum flooding on streams overlying Lampton Dome would inundate about 43 hectares (107 acres), or approximately 10 percent of the projected area above the -610-meter (-2,000- ft) -MSL salt dome contour. The most significant flood potential at the site is from backwater effects on Elbow Branch created by the presence of Lake Bill Waller.

Base flow for streams in the vicinity of Lampton Dome suggests that the hydraulic properties of the surficial geologic unit in this area, the Hattiesburg Formation, are relatively high and that local recharge is also high. The 7-day, 2-year low flow for both Upper Little Creek and Lower Little Creek in the vicinity of Lampton Dome is approximately 11 l/sec (0.4 ft^3/sec) per square mile of drainage area (Taylor and others, 1968). This value is high compared to streams throughout most of the Mississippi Study Area.

Vacherie Dome is located almost entirely within the Bashaway Creek watershed, a minor tributary to Black Lake Bayou (see

Probable maximum flooding on streams crossing the Rayburn's Dome area would inundate about 63 hectares (155 acres), or approximately 20 percent of the area defined by the surface projection of the -610-meter (-2,000- ft) -MSL salt dome contour. This flooding represents probable maximum flooding of the Fouse Bayou and Muddy Creek watersheds.

The base flow of streams in the vicinity of Rayburn's Dome is primarily derived from the Sparta Formation and suggests that the hydraulic properties of the Sparta in this area are relatively high and that local recharge is good. Seven-day, 2-year low flows reported by Speer and others (1966) for this area are typical of values reported for other streams in the study area that derive their base flow from the Sparta Formation.

Oakwood Dome is located on the Freestone-Leon County line in the Upper Keechi Creek watershed, a tributary to the Trinity River (see Figure 4-18). The dome is drained by Alligator and Mustang Creeks, which are tributaries to Buffalo Creek which, in turn, is a tributary to Upper Keechi Creek.

The topography overlying Oakwood Dome is characterized by an irregular ridge of rounded hills, forming a ring that roughly corresponds to the outline of the dome. Elevation of the top of this ridge is approximately 137 meters (450 ft) MSL on the west, south, and east sides. Within the ring is a central depression whose elevation drops as low as 91 meters (300 ft) MSL. Drainage on the east side of the ridge is into Alligator Creek, but drainage on the west side of the ridge is into Mustang Creek.

Probable maximum flooding on streams crossing Oakwood Dome would inundate about 89 hectares (220 acres) of the surface area projected from the -610-meter (-2,000- ft) -MSL salt dome contour. The calculated area of inundation is approximately 9 percent of the projected domal area. This postulated flooding represents the probable maximum inundation over the Mustang Creek and Alligator Creek watersheds.

It is expected that base flows of streams over Oakwood Dome will be lower than base flows of streams in other parts of the East Texas Study Area. Formations outcropping over Oakwood Dome are predominantly alluvium and terrace deposits and sediments of the Claiborne Group, mainly the Queen City and Reklaw Formations, with some Carrizo Formation also present. Quantitative measurements of the base flow of streams in the study area have not been made, and no historical records exist.

Keechi Dome is located in the Keechie Creek watershed, a tributary to the Trinity River (see Figure 4-18). The topography overlying Keechi Dome is characterized by gently rolling hills, with Keechie Creek running almost directly down the major axis of the dome. The highest elevation on the site is approximately 152 meters (500 ft) MSL.

The probable maximum flood for streams crossing Keechi Dome would inundate about 85 hectares (210 acres) of the projected area above the -610-meter (-2,000- ft) -MSL salt dome contour. The inundated area is approximately 17 percent of the projected domal area. This flooding represents the probable maximum inundation over the Keechie Creek subwatershed.

It is expected that base flows of streams over Keechi Dome will be the same or higher than base flows of streams in other parts of the study area. Formations outcropping over Keechi Dome are predominantly sediments of the Claiborne and Wilcox groups. Quantitative measurements of base flow of streams in the study area have not been made, and no historical records exist.

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REVIEW COMMENTS TO

DRAFT REPORT WITH REPLIES

Comments on Second Draft, Geologic Area Characterization Report Volume I, Introduction, Background and Summary, by Mississippi Department of Natural Resources, Bureau of Geology, April 1981, with Replies

1. The conclusions listed under Area Characterization Summary in Volume I are too brief and generalized, and in some cases are not complete. A person who read only these conclusions would be misled about the suitability of salt domes for a nuclear waste repository.

In the final report, the Area Characterization Summary has been expanded into a full chapter.

2. There are internal inconsistencies in the report. While this is understandable for a report that utilized so many different subcontractor's reports, it does point out how unevenly the study was conducted in each study area and at each individual salt dome.

Every effort has been made to remove internal inconsistencies in the final report.

3. Alternate geologic interpretations are not adequately presented. In certain cases it is possible to use the given data and illustrations to argue for a conclusion exactly opposite that presented in the text of the report.

Alternate geologic interpretations are presented where plausible and substantiable. It is difficult to respond to this comment without specifics.

4. The selected boundary of the Mississippi Study Area is inadequate. The area encompasses 1440 square miles, but Cypress Creek and Richton Domes are both within two or three miles of the boundary. Surely we are more in need of a geologic and hydrologic characterization, for example, in southeastern Jones County only two miles from Richton Dome than for the central part of the study area which is 20 miles from any of the three study domes.

The Mississippi Study Area was selected to encompass an area which included the domes of interest, not necessarily to totally include the areas which influence the domes or the areas which are influenced by them. The area studies have provided valuable insight into the geologic and hydrologic characteristics of the area, and have provided a basis, which did not previously

exist, for defining the areal extent of Location and Site Characterization studies.

5. Two "worst possible cases" are presented in Volume I, Section 2.6, entitled "Maximum Potential for Erosion and Denudation". The calculations presented are based on (1) a complete melting of the world's ice sheets and glaciers resulting in a rise in sea level (see Table 2.6-1), and (2) a lowering of a sea level caused by a period of major glaciation (see page 2-139 and Table 2.6-1).

   The "worst case" situation concerning erosion in the study area as a result of sea-level lowering is deficient in two ways. First, the calculations did not take into consideration the published precise leveling data of Holdahl and Morrison (Tectonophysics, v. 23, p. 373-390, 1974), which indicates uplift of the modern surface of two to four mm/year across portions of the Mississippi study area. If these figures had been added into the computations, the likelihood of the Mississippi salt domes being breached would have been greatly increased. Secondly in the discussion of erosion and stream downcutting due to glaciation and sea level reduction, a gradient of one foot-per-mile for the streams was used in the calculation. However, a general summary of surface water in the Gulf Interior Region study area contains the following sentence on page 2-179 of Volume I: "Streambed slopes range from more than 30 feet-per-mile for tributaries to less than 3 feet-per mile for major rivers". (emphasis added) If a figure of 3 or even 2 feet-per-mile had been used in the calculations (representing existing conditions) instead of one foot-per-mile, the likelihood of the Mississippi salt domes being breached would have been greatly increased.

   During a briefing by the Department of Energy and Law Engineering Testing Company held in Jackson, Mississippi, in September 1980, Dr. Clay Durham was asked to comment on the Holdahl-Morrison report. Although he discounted the validity of this report, there are several references in the Area Characterization Reports to it (Volume I, Section 2.6; Volume II a, page 6-57; Volume IV A, page 12-42); apparently data from this report were used in the area characterization studies for Texas. The data were published in a reputable journal and to our knowledge have not been retracted or refuted in print. On page 12-42 of Volume IV A it is stated that Cornell University is currently reviewing the Holdahl-Morrison data; we have not seen a copy of the Cornell report. A verdict on the Holdahl-Morrison data is vital to any conclusions about the probability of breaching of the Mississippi salt domes that may be derived.

The implications of the Holdahl-Morrison data with respect to rapid uplift in the Gulf Coastal Plain are not supported by geomorphic or other evidence. The Cornell University study is ongoing. Location and Site Characterization studies will further address the problem in an attempt to resolve it once and for all.

BEST DOCUMENT AVAILABLE

The interested reader is referred to the report prepared by LETCo consultants entitled Maximum Potential Erosion and Inundation of Seven Interior Salt Domes for a complete treatment of erosion and inundation. Section 2.6 has been removed in the final report.

The use of stream gradient of one-foot-per mile is more conservative than the use of 3 or even 2 feet per mile.

6. The overview of Interior Salt Basin seismicity (Volume I, Sec. 2.5.1) states the following on page 2-98: "Except for the New Madrid earthquake series (1811-1812), surface displacement during historic earthquakes has not occurred in the southcentral United States. Furthermore, the earthquakes of the Interior Salt Basins are not known to be associated with specific tectonic structures." These statements, while true, are misleading because they do not state the complete facts. In the New Madrid seismic area (roughly equivalent to the New Madrid Fault Zone region of the ACR), the U.S. Geological Survey has found physical evidience in near-surfce sediments of perhaps three episodes of sediment disruption in the last two thousand years. The lack of cases of surface displacement during historic earthquakes in the southcentral U.S. may simply be an artifact of the short period of recorded history (less than 300 years) in this area.

The lack of a long period of recorded history is indeed a problem for seismologists trying to piece together the seismotectonic relationships in the southcentral U.S. Seismic activity in the Middle East, where a long recorded history does exist, has been shown to be episodic. The episodic nature of seismic events in the Middle East has been explained by crustal plate movements. In the South-central U.S., horizontal plate movements do not appear to be the source of known earthquakes. The Mississippi ACR domes are in a seismotectonic region in which the predominant crustal movements have been related to subsidence. The regional subsidence may have been episodic, but only in terms of 10,000 to million year periods. Earthquakes associated with horizontal plate movements normally have episodic periods less than 1,000 years.

There are not any obivious topographic features which would suggest recent periods of major seismic events, generated from tectonic structures, near the Mississippi candidate domes or within the Interior Salt Basin seismotectonic region.

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7. Also, earthquakes need not cause surface displacements to cause significant motion of the ground and structures in areas of unconsolidated sediments such as Mississippi. While it is true that earthquakes in the Interior Salt Basins are not known to be associated with specific tectonic structures, several locational correlations may be made. For example, the seismically active areas of the Clarke County and Bolivar County areas are located on or near the Pickens-Gilbertown Fault Zone and the roughly coincidental line of abrupt change in depth to basement. Although an association of earthquakes with specific tectonic features near the salt basins has not been proven, concerns about possible associations have not been allayed.

Law Engineering earth scientists feel that the referenced earthquakes are related to the Pickens-Gilbertown Fault Zone. They also feel that oil and gas production in the related structural traps may have activated these faults. The test of this induced seismicity would be a microseismic array over production areas and nonproduction areas within the fault zone.

8. Section 2.5.1 of Volume I discusses the "seismotectonic regions" approach to seismic risk analysis that was used in area characterization. The "regions approach may give an incomplete picture of seismicity of Mississippi. The Mississippi study area is in the Interior Salt Basin Region, which obviously has had less earthquakes than regions to the north. However, the only earthquake specifically mentioned in the text in this region is the questionable 1891 Rush, Texas event. Larger, more recent earthquakes have occurred much closer to the Mississippi salt basin (or had more severe effects on Mississippi), though not necessarily in the same "region": For example the Modified Mercalli intensity VI-VII Batesville, Mississippi, earthquake of 1931 and the intensity VI Greenville, Mississippi earthquake of 1967 are both in the "Ouachita Region", and were not adequately considered relative to the Mississippi study area. The New Madrid earthquakes of 1811-1812 and the 1886 Charleston, South Carolina earthquake were felt throughout Mississippi. Even the Anchorage, Alaska, earthquake of 1964 affected water levels in observation wells in Mississippi and broke the riverboat Sprague from its moorings in Vicksburg. Over 50 earthquakes with epicenters outside Mississippi have been felt in some part of this state in the last 250 years or so.

The intent of the "seismotectonic regions (STR) approach" is not to give a complete "picture of seismicity in Mississippi"; STR's are not confined to state boundaries. STR's are based on regional geologic and seismologic character. All of the STR's within 1,000 miles of each Mississippi site contributed to the Earthquake Recurrence Analysis and ultimately the maximum MMI at each site.

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9. Section 12.2.4 of Volume IV A discusses the seismicity of the study area; it offers very little not already discussed in Volume I. All that is different is a list and map of Mississippi area earthquakes and an analysis of the possibility that two locally-felt post-1930 earthquakes may have been induced by operations at some oil and gas fields. The latter analysis was done because oil-field activity has been known to trigger eathquakes (at some localities) and because no structures or tectonic features near the Mississippi study area are known to have generated earthquakes. None of several legitimate associations of earthquakes with structural features in Mississippi was analyzed. An association of earthquakes with these features has not been proven, but neither has it been disproven; the Area Characterization Report is deficient in not having properly analyzed known facts.

One of the purposes of the ACR was to correlate earthquake epicenters with geologic structures (2.5 and 12.2.4.3). All apparent associations between earthquakes and geologic structures were evaluated. This analysis of possible associations produced only one credible correlation, and that was the O&G production areas. The discounted associations were not documented in this report. Since the author of the above comment did not list or reference any of the "legitimate associations" or "known facts", one is left without clue as to what they are.

10. The earthquake frequency analysis given in Sec.2.5.2 of Volume I is the source of the identification of a maximum credible earthquake for the Interior Salt Basin Region. That maximum is intensity VI because that was the intensity of the largest event recorded in the region. Since the Area Characterization Report admits that the boundaries of the regions were drawn somewhat arbitrarily (see pages 2-99 and 2-103: "They are not always delineated by obvious geologic or geophysical features."), and for other reasons already stated, an intensity VI earthquake is not a conservative estimate for a maximum credible earthquake for the candidate domes. The section also states that an intensity VI earthquake would have a "ground acceleration at the surface of 0.06g." It does not state whether this is a vertical or horizontal acceleration.

The maximum credible ground motion is presented as horizontal motion. The seismotectonic region boundaries are represented by transition zones, however they are not arbitrary. The approach used to establish the maximum credible earthquake (MCE) has been approved by the NRC for licensing purposes. Alternative procedures for calculating that MCE would require substantial clarification, justification, and NRC approval.

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11. Although evidence about several locations of upward flow of groundwater at Mississippi domes is mentioned at more than one place in the ACR, the serious implications of this movement are not emphasized adequately in the conclusions for Chapter 14 of Volume IV A (Mississippi study area) or in the conclusions in Volume I (Gulf Coast Salt Domes Project).

Ground-water flow in the vicinity of Richton and Cypress Creek Domes has been emphasized in the final report. The Area Characterization summary has been expanded in the final report.

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